Towards a methodology for integrated freeform manufacturing systems development with a control systems emphasis

Jacquelyn K. Stroble

TOWARDS A METHODOLOGY FOR INTEGRATED FREEFORM MANUFACTURING SYSTEMS DEVELOPMENT WITH A CONTROL SYSTEMS EMPHASIS

by

JACQUELYN KAY STROBLE

A THESIS

Presented to the Faculty of the Graduate School of the

UNIVERSITY OF MISSOURI-ROLLA

In Partial Fulfillment of the Requirements for the Degree

MASTER OF SCIENCE IN MANUFACTURING ENGINEERING

2007

Approved by

Dr. Frank Liou, Co-Advisor

Dr. Kelvin Erickson, Co-Advisor

Dr. Venkata Allada

PUBLICATION THESIS OPTION

This thesis consists of the following two articles that have been submitted for publication as follows:

Pages 3-44 are intended for submission in JOURNAL OF MANUFACTURING SYSTEMS, SOCIETY OF MANUFACTURING ENGINEERS

Pages 45-67 were submitted and accepted to the SOLID FREEFORM FABRICATION SYMPOSIUM

ABSTRACT

A variety of fully integrated Freeform Fabrication (FFF) systems have been developed, a selected group for research and several for commercialization. The design methodology behind most of them is not documented, standardized, or rational. It is important to understand that the final product from any integrated system is affected not only by the unit manufacturing processes themselves, but also by the extent the individual units are assimilated into an integrated process. Thus, a scheme consisting of eight steps and the salient five elements necessary to create or retrofit an existing system to achieve an Integrated Freeform Manufacturing System (IFFMS) is proposed in this thesis. Specifically, mass-change, deformation and consolidation unit manufacturing processes are emphasized, as the priority is focused on rapid prototyping (RP) technologies. To illustrate the proposed scheme, the University of Missouri-Rolla (UMR) Laser Aided Manufacturing Process (LAMP) system is presented.

Subsequently, the automated control system framework for a hybrid laser metal deposition system consisting of five phases is presented. The groundwork for an automated control system involves the integration of software with a real time controller, sensors and actuators. Key control parameters for a laser metal deposition process are reviewed and their incorporation into the software is correlated to the goal of an automated hybrid system. The first phase of the framework was completed and the results are presented in the second paper. Further development of the framework phases is elucidated and the future work for the control system implementation is provided.

ACKNOWLEDGMENTS

I would like to express my sincere gratitude to my co-advisors Dr. Erickson and Dr. Liou for their outstanding support and encouragement throughout the duration of my masters research. Without their support my work would have not been possible.

I would like to express my sincere appreciation to my committee member Dr. Allada for his advice and enthusiasm for my research. His comments and suggestions have been very helpful. My sincere thanks to Dr. Landers for his guidance with control systems and his advice for conducting this research. I am extremely thankful for Dr. Ruan, Todd Sparks, and Mitch Cottrell for always providing an answer to all my questions and technical assistance when I need it most.

I would like to express my sincere and heartfelt appreciation to my parents and grandparents, whom have supported me in all my endeavors. I am also sincerely grateful for those friends who are closest to me here in Rolla. All of you have made me a better person, kept me from working so hard that I sacrifice my health, and have encouraged me to keep smiling and laughing.

I am extremely grateful to Dr. Erickson for the opportunity to teach the Factory Automation Lab in the Electrical Engineering Department for three semesters. I enjoyed it very much and greatly enjoyed teaching the Factory Automation class in his absence. The research assistantship support extended by Dr. Liou and the Manufacturing Engineering Department is also greatly acknowledged.

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1. INTRODUCTION

Rapid prototyping is a phenomenon that has been sweeping across the manufacturing industry for the past decade and is shortening product design times, allowing digital prototypes to be held in ones hand, and in some cases provides temporary parts to an everyday process. Several companies have reaped these benefits of rapid prototyping by utilizing it in their product design stage or in the mass production of small plastic parts. Although the rapid prototyped part does not have all the qualities or attributes of the desired finished product, it allows one to think outside the typical design realm and push the limits to achieve impressive designs.

There are three basic types of rapid prototyping: additive, subtractive, and formative. All of these can be automated to process a stereolithography (STL) file, which spawns from a CAD file or 3-D digital representation of the part. Several materials are available for rapid prototyping such as, plastics, metals, sand, wax, paper, etc., which start as a solid, liquid, or powder. With rapid prototyping systems the possibilities for creation are endless, plus, they can be extended to create integrated manufacturing systems.

The Laser Aided Manufacturing Process (LAMP) lab at the University of Missouri-Rolla did just that. Two types of rapid prototyping, a laser metal deposition process and machining process, were merged to create the LAMP system, thus creating an integrated manufacturing system. The LAMP system, when it was being built in

1999, was a new, advantageous approach to using rapid prototyping technology. Moreover, there were not manuals or well-documented methods for creating an integrated system from a current rapid prototyping system or from the bottom up. The same applies to process planning software, and the control system hardware and software configurations. Therefore, a risk was taken in building something that had not existed before and success was the result after many obstacles were overcome. Furthermore, this research and a need stated by the National Research Council (NRC) prompted for an integrated manufacturing system construction methodology to be developed, along with a method for developing a robust control system for rapid manufacturing systems.

Integrated manufacturing systems have paved the way for fast, flexible, and reliable manufacturing of products in a variety of materials. It will only become further integrated into modern manufacturing processes in the future. Allowing more intricate, complex, and significant contributions to be made to the manufacturing engineering design domain.

PAPER I

A SCHEME FOR DEVELOPING AN INTEGRATED FREEFORM MANUFACTURING SYSTEM (IFFMS)

J.K. Stroble[1], Dr. J. Ruan[2], Dr. F.W. Liou[1]
[1]Manufacturing Engineering
[2]Mechanical and Aerospace Engineering
University of Missouri – Rolla, Missouri, U.S.A 65401
Email: jksmr6@umr.edu, jruan@umr.edu, liou@umr.edu

ABSTRACT

Freeform Fabrication (FFF) and additive fabrication technologies have recently been extended to include subtractive processes to achieve a variety of fully integrated Rapid Manufacturing (RM) systems. However, the conceptual and physical design methods required to construct these systems are vaguely described or not mentioned at all. The National Research Council (NRC) has stated a need for the development of a standard for unit manufacturing process (UMP) integration. The final product is affected not only by the unit manufacturing processes themselves, but also by the extent the individual units are assimilated into an integrated process. Thus, a scheme consisting of conceptual and physical steps, and the salient five elements necessary to create or retrofit an existing system to achieve an Integrated Freeform Manufacturing System (IFFMS) is proposed in this paper. To illustrate the proposed steps, a laser aided manufacturing process (LAMP) system is presented.

Keywords

Integration; CNC; Laser cladding; Rapid Manufacturing (RM); Rapid Prototyping (RP); Freeform Manufacturing (FFM); Solid Freeform Fabrication (SFF); Additive fabrication

1. INTRODUCTION

Unit Manufacturing Processes (UMP) have continued to revolutionize the manufacturing industry since their introduction. UMPs are the addition of value to raw materials as those raw materials are transformed into finished products. The physical process focus of this paper will be the Rapid Prototyping (RP), also referred to as Solid Freeform Fabrication (SFF) or Freeform Fabrication (FFF), branch of UMPs includes mass-change, deformation, and consolidation process families. Through the utilization of RP, designers and engineers alike can quickly create geometrically complex or intricate objects without the need for elaborate machine setup or final assembly. With RP, objects can be made from multiple materials to produce composites or functionally graded materials that are varied in a controlled fashion at any location in an object. The construction of complex objects is reduced to a manageable, straightforward, and relatively fast process. Since the introduction of rapid prototyping, its properties have resulted in the wide use of RP technology as a way to reduce time-to-market and increase design freedom in manufacturing.

In an effort to shorten the time-to-market, decrease the manufacturing process chain and cut production costs, research has aimed at the integration of multiple UMPs into one machine; meaning less production space, time, and manpower. Combining UMPs leads to the creation of Integrated Freeform Manufacturing Systems (IFFMS). The IFFMS have all the same features and advantages of RP systems, plus provide a new set of features and benefits. For instance, metallic parts made by an additive layer-by-layer process typically have a lower quality surface finish, which needs machining to achieve a quality standard or desired finish. Thus, combining a machining center and an additive RP process seems logical, to reduce time lost to transporting the deposited part to another location and reclamping it for further processing. Moreover, integrated systems are increasingly being recognized as a means to produce parts in material combinations not otherwise possible and have the ability to fabricate complex internal geometries, which is beyond anything that can be accomplished with subtractive technologies alone. Internal geometries such as complex conformal cooling channels provide better product thermal performance and RP processes can create them with ease, giving the manufacturer a better product with little extra cost. In short, additive, subtractive, and formative RP technologies are going to revolutionize the manufacturing industry with the new method of integrated systems. This approach to manufacturing will have profound implications on the way designers are accustomed to working and will eliminate most design for manufacture considerations.

This new class of technology has been slowly picking up momentum as manufacturers and customers dream up more complex and better products, which require more complex and advanced equipment. Many have asked research teams at universities to assist in creating the needed advanced technology. For example, the aerospace industry wanted to deposit 3D titanium jet parts because machining titanium creates extensive waste and cost. The deposited parts need to be machined for better surface finish directly after deposition, so an integrated system, consisting of laser metal deposition and machining, was developed. Consequently, the Unit Manufacturing

Process Committee of the National Research Council (NRC) noticed this trend and stated a need for the development of standards for UMP integration, similar to the efforts made within the semiconductor equipment and materials standards committee (NRC 1995).

UMP families noted by the NRC for integration includes mass-change, phase-change, structure-change, deformation, consolidation and the forthcoming integrated. An IFFMS is comprised of five elements: production planning software, control system, motion system, UMP, and a finishing process. These integrate into one manufacturing system and work together seamlessly. The finishing process is also a UMP, but is labeled differently to emphasize its individual importance for developing a manufacturing system. Without it, the system could not claim manufacturing status. However, current literature does not address mechanical, electrical, software and control interfaces between unit manufacturing processes that would allow engineers and designers to easily select combinations for integration. Therefore, steps, combination chart, breakdown of the five elements, common obstacles and how to overcome them to achieve an IFFMS are all presented in subsequent sections. (Note, this paper is only a stepping-stone to a perfected IFFMS.) Various systems demonstrate integration and fit the need stated by the NRC, but do not fit the scope of this paper, for instance the hybrid measurement system (Shiou and Chen 2003) and hybrid electro chemical discharge machining system (Mediliyegedara et al. 2005). Specifically, deformation and consolidation processes will be the emphasis of this paper, as the priority is focused on RP technologies. An example to further illustrate the details of creating an IFFMS is presented in Section 5.

1.1 Literature Review

To avoid confusion an overview of basic terms is given first. Any process that results in a solid physical part produced directly from a 3D CAD model can be labeled a rapid prototyping process (Kalpakjian and Schmid 2003). Equally, a part that is made in a layer-by-layer fashion is labeled an RP process, and typically called solid freeform fabrication (SFF), additive manufacturing or layered manufacturing. It must be noted that not all RP processes build in a layer-by-layer fashion. Forming, casting and other deformation RP processes usually happen in a one time intensive step as opposed to a build sequence of layers that begins with a 3D CAD model, and which falls under the subcategory of freeform fabrication (FFF). Therefore, the term rapid prototyping is an umbrella covering a wide range of subcategorized processes. Considering another broad term, manufacturing is the process of converting raw materials into a finished product. When it is compared to RP all that is missing is the finishing aspect. Thus, when RP was paired with a subtractive or finishing process that directly produces a finished product, two new terms were born, rapid manufacturing and direct manufacturing (Grenda 2007). Both terms are appropriate and express the direction and focus of this paper. These systems have been called hybrid, agile, or intelligent, but the best way to describe them is simply integrated. Multiple unit manufacturing processes are being combined into one machine, but do not operate simultaneously, and thus are not a hybrid system. They are separate processes within the manufacturing system. Again, RM systems are one level above RP systems because they provide a complete product ready for use by adding a finishing process after the traditional RP process, and thus are akin to integrated systems.

1.1.1 Synopsis of Current Rapid Manufacturing Systems

Rapid manufacturing systems are reviewed here to give the designer an idea of what has been successful and to uncover where there is a possible opportunity. The vast domains of SFF and FFF have provoked many to test boundaries and try a new concept, in an attempt to discover the next best process that will play a key role in advancing RM technologies. Academic and industry researchers alike have been developing RM systems with a basis of deformation and consolidation RP technologies and several IFFMS have come about. However, the design strategies were not published. On the other hand, a few approaches taken to develop reliable RM processes that deliver consistent results, the majority based on consolidation processes, have published a modest guide on their system design. Other RM approaches utilize laser wire welding, welding, hydroforming, casting, and even variable lamination manufacturing.

Beam-directed technologies, such as laser cladding, are very easy to integrate with other processes. Most have been integrated with CNC machining centers by simply mounting the cladding head to the CNC z-axis. Kerschbaumer and Ernst (2004) retrofitted an Röders RFM 600 DS 5-axis milling machine with an Nd:YAG laser cladding head and powder feeding unit, which are all controlled by extended CNC-control. Similarly, a Direct Laser Deposition (DLD) process utilizing an Nd:YAG laser, coaxial powder nozzle and digitizing system as described by Nowotny, et al. (2003) was integrated into a 3-axis Fadal milling machine. The Laser Aided Manufacturing Process (LAMP) lab also integrates a laser cladding head with a Fadal 5-axis machining center, along with a National Instruments real-time control system and several sensors to aid in the process (Boddu et al. 2003). Laser-Based Additive Manufacturing (LBAM) researched at Southern Methodist University, is a technique that combines an Nd:YAG laser and powder feeder with a custom built motion system that is outfitted with an infrared imaging system (Hu et al. 2002). This process yields high precision metallic parts with consistent process quality. These four systems perform all deposition steps first, and then machine the part to the desired finish, consistent with conventional additive fabrication.

Non-conventional additive processes demonstrate advanced features, alternate additive and subtractive steps, filling shell casts, etc. A hybrid RP process proposed by Hur et al. (2002) combines a 6-axis machining center with any type of additive process that is machinable, a sheet reverse module, and an advanced process planning software package. What differentiates this process is that the software decomposes the CAD model into machining and deposition feature segments which maximizes the CNC advantages and significantly reduces build time and increases shape accuracy. Laser welding, another hybrid approach, involves a wire feeder, CO_2 laser, 5-axis milling center and a custom PC-NC based control unit that has been used to produce molds for injection molding (Choi et al. 2001). Hybrid-Layered Manufacturing (HLM) as researched by Akula, et. al (2006) integrates a TransPulse Synergic MIG/MAG welding process with a conventional CNC to produce near-net shape tools and dies. This is direct rapid tooling. Welding and face milling operations are alternated to achieve desired layer height and to produce very accurate, dense metal parts. A comparable process was developed at Fraunhofer IPT named Controlled Metal Build-up (CMB), in which, after each deposited layer the surface is milled smooth (Klocke 2002). However, CMB utilizes a laser integrated into a conventional CNC.

Song and Park (2006) have developed a hybrid deposition process, named 3D welding and milling because a wire-based gas metal arc welding (GMAW) apparatus has been integrated with a CNC. This process uses gas metal arc welding to deposit faster and more economically. Uniquely, 3D welding and milling can deposit two materials simultaneously with two welding guns or fill deposited shells quickly by pouring molten metal into them. The mold Shape Deposition Manufacturing (SDM) system at Stanford also uses multiple materials to deposit a finished part, however, for a different purpose (Cooper 1999). A substrate is placed in the CNC and sturdy material such as UV-curable resin or wax is deposited to form the walls of a mold, which then is filled with an easily dissolvable material. The top of the mold is deposited over the dissolvable material to finish the mold; once the mold has cooled down the dissolvable material is removed, but replaced with the desired part material. Finally, the sturdy mold is removed to reveal the final part, which can be machined if necessary. Contrary to the typical design sequence, Jeng et. al (2001) constructed their own motion and control system for a Selective Laser Cladding (SLC) system and integrated the milling head, which smoothes the deposition surface after every two layers. Clearly, each system has its advantages and contributes differently to the RM industry.

Although using a CNC for a motion system in the RM system is most common, a robot arm can easily be substituted. This is the case with SDM created at Stanford University (Fessler et al. 1999). The robot arm was fitted with an Nd:YAG laser cladding head which can be positioned accurately, allowing for selective depositing of the material and greatly reducing machining time. Integration of a handling robot with a hydroforming station and laser station has proved to shorten the process chain for the manufacture of complex hollow parts (Kreis et al. 2005). The robot has significantly reduced positioning errors and time between operations. Additionally, the combination of tube and double sheet forming processes allowed for multiple materials to be used in one step and can be optimized for any application.

Most of the aforementioned systems have been built with versatility in mind and could be set-up to utilize multiple materials or adapted to perform another operation. However, there are some RM systems that are innovative and have very specific operations and capabilities. The precise cast prototyping (PC_{Pro}) system takes a novel approach to forming and casting technologies (Himmer et al. 2005). Saving space by integrating a machining center with a casting system, saving time by incorporating two molds, and saving money by providing a fully customizable casting solution. The difference is that the casting mold starts as a block but is machined to specification, a polyurethane material is dispensed into the mold, and once it has cured the polyurethane is machined to yield a precise 3D prototype or part. For large sized objects, up to 3 ft. x 5 ft., there is the variable lamination manufacturing (VLM-ST) and multi-functional hotwire cutting (MHC) system (Yang et al. 2005). This system converts polystyrene foam blocks into 3D objects by utilizing a turntable while cutting them with the 4-axis MHC process; if the object is bigger still, multiple pieces are cut and put together.

1.1.2 Synopsis of Current Manufacturing Design Mythologies

The design strategy behind several of the aforementioned RM systems was not emphasized and documented. Thus, a key piece of information for RM systems is missing and prevents researchers and designers from easily designing and constructing an

IFFMS of their own for production research, materials research, controls research, etc. Nevertheless, an integrated system can be likened to a mechatronic system in that many mechanical, electrical and software pieces are put together to make a whole. An integrated method for the conceptual design of mechatronic products (Gausemeier et al. 2001) is a significant design strategy that couples all those pieces in the most efficient way. Gausemeier starts with the product development process in mind and stresses the role of modeling and simulation of product properties, resulting in cross-domain interaction. This design approach, however, does not lead the reader though the physical implementation phase. However, a notable attempt at bridging design and implementation is the eXecutable Specification (XSpec) method for designing manufacturing systems (Judd et al. 1991). The XSpec software methodology was built on the principles of object-oriented design and programming, and rapid prototyping, in that, each design model involves building an executable of the software and hardware of the future system. By modeling each component on the factory floor, all messages that pass between them, simulating the factory and debugging the factory design makes this strategy great for large scale, evolvable systems, by covering a breadth instead of depth of options. Judd drives home the same vital point; the more time spent working on design of the implementation, the shorter the integration and debug times are (Judd et al. 1991). Although, XSpec does not allow integration of unit manufacturing processes into the same footprint as expected for an IFFMS, it can integrate many different types of unit processes into a factory floor layout and allow for reconfigurable systems.

Reconfigurable manufacturing systems (RMS) are those that emphasize modularity, integrability, convertibility, diagnosability and customization (Mehrabi et al. 2000), which are many of the same advantages of the IFFMS. The RMS is geared towards a large scale system that includes conveyors, supply chains, packaging, etc. just like flexible manufacturing systems (FMS). However, the main principles can be adapted to a smaller system and utilized in a different manner. A more mathematical strategy for system design is the unified structural-procedural approach (USPA) (Macedo 2004). Again, this type of strategy is for large scale systems, but also takes into account that many operators and their roles in the process are applicable to the design of an IFFMS. However, Macedo makes a significant point about integration, "The desired efficiency is not reached when the machines, operators and materials required by the manufacturing process are scaled up and put together without an adequate integration." (Macedo 2004) He addresses the common, inherently flawed design strategy of just buying equipment for a good price and then trying to design a system with the random pieces. Thinking about building blocks, one cannot build a sturdy structure if the blocks have circular, square, and triangular shaped connectors. A design should always begin with a conceptual phase to prevent future setbacks, such as the pieces not fitting together, which is exactly what is proposed and discussed in the subsequent sections.

2. SCHEME TOWARD COLLECTIVE FREEFORM FABRICATION INTEGRATION

This proposed scheme consists of a design strategy of eight steps and a set of five elements, key to every IFFMS. Each of the steps is comprised of a detailed method to guide those wanting to construct a new system or retrofit a current one. A brief description of each step is presented here and all details are contained in the Conceptual and Physical Methodology Sections. The steps of the integration scheme, presented in Fig. 1, are to happen in sequential order. Furthermore, the five elements to every

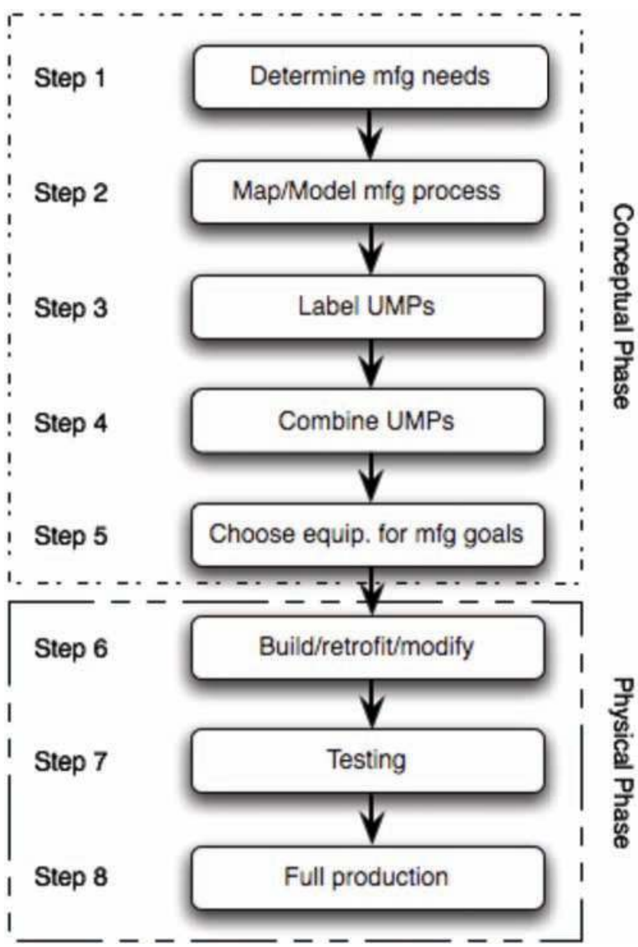

Figure 1: Proposed Integration Scheme

IFFMS that are equally as important are shown in Fig. 2. It must be kept in mind that the salient five elements work as a collective and should be given equal attention throughout the integration scheme.

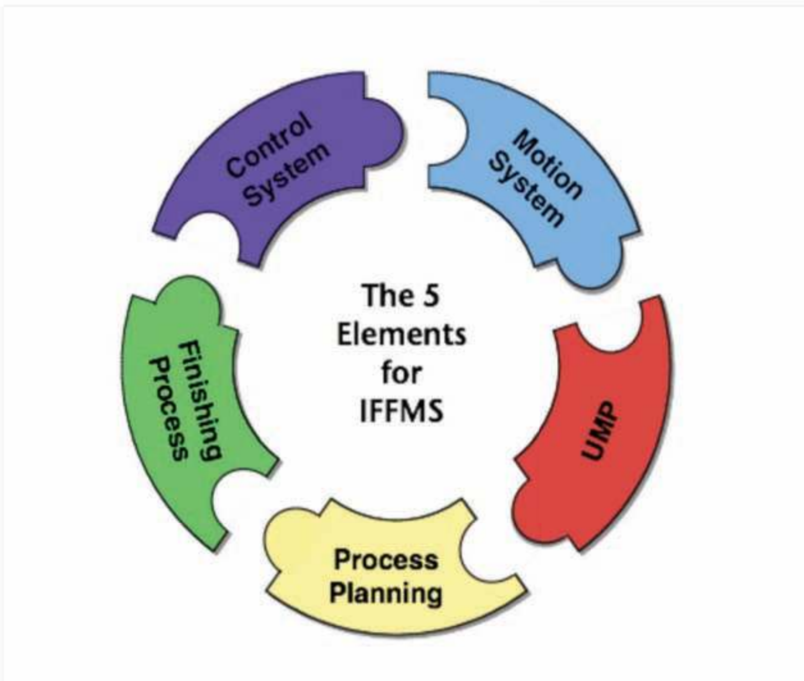

Figure 2: Five Elements of an IFFMS

2.1 Steps – Conceptual

Step 1: As with all good designs, the first step is to determine the manufacturing needs of the internal and external customers. A series of questions need to be answered:

- What features does the product entail? Are they embedded?
- What materials will the product be made of?
- How small are the feature sizes?
- Is the product customizable for each customer? (i.e. no two are the same)

This is a short list, but covers a large range of information needed to move on to the next step.

Step 2: The objective in this step is to create a process map or model of the desired manufacturing system as defined by the needs from Step 1. Process maps and models are visual aids in the design process and allow for anyone to clearly understand what the system does or will do.

Step 3: The third step of the conceptual phase is to label, mark, designate, make clear, the unit manufacturing processes. This will enable, visually and conceptually, the ability to create an integrated system. There are 5 main types of unit manufacturing processes as categorized by the NRC that cover the majority of manufacturing methods taking place in this millennia: mass-change, phase-change, structure-change, deformation, and consolidation (NRC 1995).

Step 4: In the event that two or more of these processes can be combined, the fourth step may be executed. Combining the UMP, based on certain criteria, will aid in Step 5 decision making.

Step 5: The last conceptual phase step is choosing equipment (hardware and software) that will achieve the desired manufacturing system laid out by Step 4.

2.2 Steps – Physical

Step 6: In step six the system is built or a current system is retrofitted with new equipment.

Step 7: The newly built system is tested to ensure all hardware and software are working together seamlessly. This will aid in figuring out if anything is missing or additions that might be needed. A considerable amount of time should be allotted for the physical phase, to debug and work through challenges that may arise along the path to a successful IFFMS.

Step 8: The final step is to start full production using the newly built system.

2.3 Five Key Elements of Every Integrated Freeform Fabrication Manufacturing System

Every integrated freeform fabrication manufacturing system is comprised of five elements as summarized in Table 1. Process planning, motion system, control system, RP process, and finishing process are equally important, required, and attention should be balanced among them. The process planning software is the first element that is utilized, as it generates commands for the control system to disseminate, as an off-line process. The control system distributes the commands but also monitors feedback, depending if there are sensors involved, to ensure a quality part is produced. As the number of axes of the motion system are increased, the more complicated geometries can be realized and support material or structures can be eliminated. Additionally, the motion system executes the tool path as per the process planning software at a specified velocity. Most rapid prototyping processes produce an acceptable part, but require further processing to improve the surface finish, microstructure, or remove the substrate. Thus, a finishing process is needed to transform the traditional RP system into an integrated RM system. The finishing process is the last step to creating a manufactured part, but could be repeated if needed. For example, a part could have multiple sections that require an RP

Table 1: Summary of the Five IFFMS Elements

Element	Description	Example
Process Planning	A method that determines the tool path or motion system movements from a 3D CAD model.	CAD/CAM, layer-by-layer build path
Motion System	An apparatus with two or more axes and holds the substrate or UMP device.	Robot, CNC machine, X,Y linear table
Unit Manufacturing Process	Any manufacturing process that adds value to raw materials by transforming them into finished products.	LENS, SLS, FGM, etc. (See Table 2)
Finishing Process	An operation executed on parts formed by a UMP to gain desired final finishes and tolerances.	Wire EDM, EDM, CNC machining
Control System	A mechanical, optical, or electronic system that is capable of open or closed-loop control. Typically an on-line system, constantly monitoring with sensors and reacting based on feedback.	PC with DAQ cards, CNC extended control, NI real-time systems with DAQ cards

and then finishing in a cyclic pattern. The UMP and finishing processes also accept commands from the control system to produce the desired part.

3. CONCEPTUAL METHODOLOGY

The conceptual phase focuses on system design and identifies integration opportunities. Again, to reiterate its importance, more time spent in the conceptual design phase will save time and prevent future setbacks during the physical phase. The, following are the details needed to perform each of the conceptual phase steps.

3.1 Step 1 - Determine Manufacturing Needs

Many different approaches have been presented to achieve an integrated manufacturing system, however they all have the same underlying principles.

- Two or more UMP are combined to save time, space, resources, manpower
- Unified control system
- Part is handled less
- A final product is the result

Therefore, many combinations of unit manufacturing processes can be combined to create an IFFMS; all of which have the five elements described in Table 1. An IFFMS design needs a starting point. Accordingly, the first step is determining the manufacturing needs and goals disregarding equipment and anything physical. This is strictly a conceptual activity that should not be biased by physical equipment. Furthermore, focusing attention to complete Step 1 correctly is key to avoiding several unneeded iterative changes later in the design.

3.2 Step 2 - Map/Model All Manufacturing Process Steps From Start to Finish

This step is detailed and time intensive, but transforms customer needs into the engineering specifications needed to proceed with the design. Creating a process map or model is the key to making the rest of the design steps easy. Process maps and models are visual aids in the design process and allow for anyone to clearly understand what the system does or will do. Considering a future IFFMS, the map or model is crucial and needed to advance through the steps because there is not a physical system which can be reverse engineered and put onto paper. Thus, creating the most accurate map or model will depict the future system and provide the correct direction for following the integration scheme.

Design efforts can and should begin in a certain design manner with that mindset carried throughout the entire design process. Design is a concurrent process and in this step one should begin to consider how the five elements will accomplish the needs stated in Step 1. For manufacturing systems there are two design manners that are clear winners, a mechatronics and a modular approach. In the mechatronics approach, all electronic, mechanical, and software components are specifically designed or chosen to work and exist together synergistically (Isermann 1996). Where as, with the modular approach, components are designed or chosen and can be swapped in or out at any given time. Achieving a design with either approach requires some degree of laying out the future system. For this, there are techniques that map or model a process and provide an advantageous visual aid. A high level, detailed method is process modeling, which instructs the user to label all signals flowing from one process, station, step, or piece of equipment to completely capture the inner workings of what is being modeled (Nagel et al. 2006).

Additionally, in the mechatronics approach, there are several references dedicated to the subject as well, that are largely a part of systems engineering. These references explain the idea of mapping and modeling of a new system around personnel and how to integrate them into the process of change, but also point out common steps that are commonly overlooked or misused (Grady 1994; Martin 1997). A low level flow chart can map just about any process and demonstrate if and where the process repeats (Ahoy 1999). Flow charts can demonstrate mechatronics or modular characteristics. Petri nets lean far into the modular category. Modeling a system by Petri nets can associate a time parameter to transitions between operations, represent buffers and resources, and specify logical relationships amongst operations (Proth et al. 1997). Hence, choosing a design manner in the beginning will continuously direct work efforts to achieve the desired manufacturing system.

3.3 Step 3 - Label Each Unit Manufacturing Process

In the third step of the integration scheme, all UMPs should be labeled or clearly marked to discern if the process has integration options. As explained in Table 2, there are five families of unit processes: mass-change, phase-change, structure-change,

Table 2: Unit Process Families, Description and Examples (NRC 1995)

Unit Process Family	Description	Unit Process Examples
Mass-change	Removal or addition of material by mechanical, electrical, or chemical means	Machining, EDM, ECM, FDM, SLA, SGC
Phase-change	Production of a solid part from the liquid or vapor phase of a material	Metal casting, injection molding, Infiltration of composites
Structure-change	Alteration of microstructure, typically by thermal treatment or force	Thin coating application, surface alloying, compressive residual stress
Deformation	Alteration of solid work piece shape without changing mass or composition	Bulk forming, sheet forming
Consolidation	Consolidation of loose materials to form a solid part by interaction with an energy source	Laser cladding, powder processing, polymeric composites, welding/joining
Integrated*	Combination of two or more unit processes operating under unified control.	HLM (Akula and Karunakaran 2006), Hybrid LMD (Kerschbaumer and Ernst 2004), LAMP (Boddu et al. 2003), SLC (Jeng and Lin 2000), SMD (Fessler et al. 1999)

*Systems that are not traditional manufacturing processes deformation, and consolidation,. Determining a UMP is relatively easy. Use the unit process examples in Table 2 to aid in the decision.

For each UMP within the system design, determine which process family it belongs to and label it. Concurrently, decide which UMP satisfy the finishing process and UMP requirement of the five elements, and label them accordingly. Furthermore, if one UMP can satisfy more than one elemental requirement, that is acceptable. An example of this is when a CNC machining center is used as the motion system and also the finishing process.

3.4 Step 4 - Combine Two or More Types of Unit Manufacturing Processes

Step 4 prompts the designer to analyze the process map or model. It may not be obvious that certain unit manufacturing processes can be combined to reduce the footprint of a system. A combination chart, Table 3, denotes which combinations of the five elements have successfully worked together, with references. It in no way restricts the designer to those realized systems, rather it is encouragement that an IFFMS can be accomplished. Table 3 is a foundation to build upon. Additionally, it can aid in Step 5, as it contains combinations of control systems, motions systems, and process planning software. Note there are references for the approaches that were very successful, all of which can be found in the References Section.

3.5 Step 5 - Determine Equipment Needed to Achieve Final Product

By this point in the integration scheme, the process map or model should be clearly understood and the designer should know what equipment is needed. It should

Table 3: Unit Manufacturing Process (UMP) Combination Chart

		Motion System			Control System				Unit Manufacturing Process - (UMP)						Finishing - (UMP)				Process Planning		
		Machining Center	Robot	Custom	OEM - Built in	Commercial real-time control system	(DIY) Programming language & computing system	PLC	Wire welding	Laser wire welding	Laser cladding	Forming	Casting	Variable Lamination	Machining	Laser cutting	EDM	Hot wire	Commercial CAD/CAM package	Custom CAD/CAM package	Commercial CAD & (DIY) CAM software
Process Planning	Commercial CAD & (DIY) CAM software	1	1	1		$-R					$			1	1						X
	Custom CAD/CAM package	1	1	1		1			1	$-C	$							1		X	
	Commercial CAD/CAM package	1			1						$	$-D			1				X		
Finishing - (UMP)	Hot wire			1			1							$-Y				X			
	EDM					1					1						X				
	Laser cutting		1	1	1	0	1		1			$-K				X					
	Machining	$	1		1	1			1	1	$		$		X						
Unit Manufacturing Process - (UMP)	Variable lamination			1			1							X							
	Casting	1			1								X								
	Forming		1		1					1		X									
	Laser cladding	1	1			$-B	$-J	1	1		X										
	Laser wire welding		1	1			$-C		1	X											
	Wire welding		1				$-Z		X												
Control System	PLC	1					1	X													
	(DIY) Programming language & computing system	1		1	1		X														
	Commercial real-time control system	1		1	1	X															
	OEM - Built in	1	1		X																
Motion System	Custom		1	X																	
	Robot	$	X																		
	Machining Center	X																			

Legend

$ - Well tested, good combination

1 - Can be integrated

X - Null Square

A - S. Akula 2006
B - M. Boddu 2003
C - D.-S. Choi 2001
D - D.Y. Yang 2002
J - J.-Y. Jeng 2001
K - O. Kreis 2005
R - J. Ruan 2006
Y - D.Y. Yang 2005
Z - Y. Z 2003

also be apparent to the designer what is available. For example, if producing metallic or plastic parts of the same material and similar geometries requiring machining, a very robust control system is not necessary. Extended CNC control would work nicely. Many of the advanced features of CNCs made in this century have been reported (Koelsch 2006). If a robust control system is needed to serve a complicated process, then a list of criteria should be made for comparison to ease the selection process. However, the designer must balance the amount of control with the needs stated in Step 1, which reiterates the importance of assessing the five elements. Further, there are systems that rely heavily upon custom software for process planning and running the control system.

Zhang, et al. (2003) have developed software that both slices the CAD model, and plans and controls the deposition parameters. The LAMP process has similar software requirements (Boddu et al. 2003; Zhang 2001). Choi, et al. (2001) use a combination of commercial and custom software. Certainly, not one way is right, rather they are all right for their application. Thus, it is up to the designer to discern what is best. Any method of decision making such as decision trees, digital logic approach, or a weighted evaluation technique can all be utilized in this step. Major obstacles, issues and how to overcome them are explained in Section 5.

Key equipment points:

- Within budget and space constraints
- Remotely controlled devices interface with control system
- Is custom software required or will commercial work?
- All five IFFMS elements are selected; some can serve dual purposes

4. PHYSICAL METHODOLOGY

The physical phase focuses on the physical implementation of the system design, resulting in an integrated system. Setbacks typically encountered when building an integrated system should not happen if enough time was put into the conceptual phase and the five IFFMS elements are balanced. The methodology of building an IFFMS proposed here is largely based on the LAMP system (Boddu 2003) ; systems by (Jeng et al. 2001), (Kerschbaumer et al. 2004), (Akula et al. 2005); and what was gathered from studying the many RP/FFF/SFF technologies available or under research.

4.1 Step 6 - Build/Retrofit Manufacturing Equipment to Achieve Integration

Trends in RM equipment have cropped up and are represented in many of the systems mentioned in the Literature Review. Consolidation unit manufacturing processes are being integrated in a majority of systems because they can be easily adapted to current equipment and processes. For instance, it is easy to combine a consolidation UMP with a CNC machining center (mass-change UMP), since both processes require a positioning device with 3-axies or more. The newer the CNC, the easier it is to integrate due to increased functionality.

Building an integrated system will require good knowledge of the equipment that is to be integrated. Furthermore, integrated systems are not commercial products and the ingenuity of the designer plays a key role in this step. The designer will need to decipher the IFFMS elements puzzle and provide a means to fit them together in the physical world. Equipment modification, unconventional use or mounting of equipment, equipment made in-house, etc. are all common to an integrated system and allow for the IFFMS puzzle to be solved. Electrically, power source availability along with routing the wires, and routing of communication/control system cables are of major concern. Also, determining if sensors (if needed) are robust enough for the new system or weather they can be used for an alternative purpose. Mechanically, platens may need to be added to equipment for adjustable mounting of new fixtures and determining if machines are robust enough for a new application or whether they can be used for an alternative purpose are of major concern. Some common concerns are listed as follows:

Hardware concerns

- Space availability
- Protection of delicate UMP equipment
- Support systems for UMP equipment
- Inert gasses for part and equipment protection
- Remotely controlling equipment with control system
- Sampling capabilities are fast enough (for real-time control systems)
- Sensor capabilities are robust enough (for real-time control systems)
- Versatility of equipment for upgrades or adding new features

Software concerns

- Process planning generated motion paths are compatible with motion system
- Matching protocols for equipment interfacing
- Intuitive graphical user interface for system control

Before actual integration, a few visualization activities can be used to prototype the system. A very detailed virtual simulation can be created to double check work envelopes and space constraints, or they can be laid out with paper and pencil. A quicker way is to create cardboard mock-ups of components and move them around until the best fit is found. Whatever the method, they will all aid in prevention of undesirable events.

4.2 Step 7 - Test Integrated System

Testing, as most know, is an iterative process. Hardware and software will need to be tested separately and then together. Software testing can also begin while the hardware is being integrated. Compatibility between commercial software packages is under the discretion of the designer and custom software will need to be extensively tested for compatibility. A large part of the testing should be focused on attaining seamless communication between the five IFFMS elements. Thus, the process planning software should generate paths for the motion system to follow and instruct the control system towards the process goal, which results in UMPs creating the desired part. One way for evaluating equipment throughput is to create static maps of input to output. This will aid in remotely controlling equipment by a stand-alone control system, where commands are typically sent by way of voltage. By mapping input to output, one can guarantee repeatable output every time. Regardless, every IFFMS should be tested without and with materials, to ensure proper communication between equipment. This will prevent damage to equipment if the wrong commands are executed. Simple geometry should always be trialed first with any of the unit manufacturing processes. After successful attempts, the level of complexity should be gradually increased, until desired results are achieved. When the IFFMS begins to show promising test results, test runs of customer parts can be performed to demonstrate production capabilities at a micro-level. This allows the customer to see first hand if the needs stated in Step 1 were carried out.

Key testing points:

- Iterative process

- Test hardware and software separate then together
- Create static maps of equipment input to output
- Simple geometry first; gradually increase complexity
- Demonstrate capabilities to customers through micro-level production

4.3 Step 8 – Full Production

The final step in the physical methodology is to begin full production of the product that was described in Step 1. Additionally, the production process should follow the process map or model created in the conceptual phase exactly, resulting in the desired finished product.

5 . OBSTACLES / ISSUES

A survey of RP technologies for direct manufacture was undertaken and identified three major obstacles: material properties, quality control, and identification of products to be produced (Hopkinson and Dickens 2001). Rapid manufacturing or integrated manufacturing, has many of the same obstacles to overcome it did five years prior, before it becomes a predominate choice in this century (Wohlers 2006). The material costs, material properties, removal of support material, habits of designers and workplace acceptance all stack up against integrated manufacturing systems. Several obstacles arise during the development of any system, but those associated with RP processes are summarized along with solutions in Table 4.

Many of the materials issues have been researched and solutions have been published, as seen by Table 4. High material costs may not be something that can be

Table 4: Common Obstacles and Solutions for the Development of Integrated Systems

Obstacle	Solution	Result	Reference
Thermal Stress in metallic parts	Fill center of part with low coefficient of thermal expansion material	Less warpage and distortion	(Fessler et al. 1999)
	Vertically section desired part, deposit every other section, deposit remaining sections		
	Infrared camera takes images of melt pool geometry to regulate laser power automatically	Constant melt pool shape and temperature	(Hu et al. 2002),(Doumanid is and Kwak 2001)
	Real-time adaptive controller to monitor volume changes in the vicinity of the heat source		(Jandric and Kovacevic 2004)
	Cooling channel plate under substrate	Deposition rapidly cools	
	Substrate with built-in cooling channel		
Adhesion/ bonding of metallic material	Pre-heat the metallic substrate	Good adhesion to substrate	(Bhimanapati 2004)
	Machine flat the top layer, every few layers in a cyclic fashion	Good bonding between layers	(Akula and Karunakaran 2006),(Klocke 2002)
Surface oxidation	Apply a steady stream of inert gas to the melt pool during deposition of metallic material	No oxidation on metallic parts	
High material costs	Use common materials if possible	Lower material costs	
	Avoid UMP processes that require proprietary materials if possible		
Removal of support material	Add more axes to motion system	No support material removal	
	Avoid UMP processes that require support material if possible		
Quality control	Sensor feedback utilized by closed-loop controllers	Automatic quality control	(Boddu et al. 2002),(Hu et al. 2002),(Doumanid is and Kwak 2001),(Jandric and Kovacevic 2004)
	Implement control charts, pareto charts, etc.	Manual quality control	(Starr 2004)
Unknown protocol	Use reverse engineering to figure out communication protocol	Easier integration	
Protection of equipment	Water cooling laser cladding head and carrier gas for a side nozzle	Prevent powder from clumping in nozzle and keep focusing optics cool	(Jeng and Lin 2000)
	Retract laser head or position it far enough away from the finishing process	Protect laser nozzle	(Kerschbaumer and Ernst 2004)
Correct mixing of material for functionally graded parts	Real-time mixing of materials with multiple hoppers	Good functionally graded parts	(Hu and Kovacevic 2003),
	Multiple deposition heads		(Song and Park 2006)
	Pre-mix materials, place in hopper		

Table 4: Common Obstacles and Solutions for the Development of Integrated Systems (cont.)

Forming/ casting issues	Add more axes to the motion system of plastic casting system	Ability to undercut and produce complicated geometries	(Himmer et al. 2005)
	Mix a solid particle sealant with the hydroforming material	Fill gaps during tube forming process	(Kreis et al. 2005)
	Cap end of tube with a flanged ring		
Poor software	Add finite element analysis into process planning software	Automatic detection of deposition complications	(Yang et al. 2002)
	Try feature based process planning	Avoids stair-step affect and hidden geometry	(Hur et al. 2002)

avoided and may be required. However, removal of support material can be avoided by utilizing a 5 or more axis motion system and by depositing non-uniform layers for a SFF process. Several of the materials issues can also be monitored by quality control methods and fixed automatically. Conversely, quality control can take on a variety of connotations as well, relating to aesthetics, functionality, material properties, control charts, Pareto charts and the list goes on (Starr 2004). Thus, it is at the discretion of the customers to communicate the factors of quality they require in a finished product. The designer can take into account quality and how it will be monitored during the manufacturing process. Other obstacles not mentioned by Wohlers or Hopkinson but covered in Table 4 are communication protocols, protection of equipment, the mixing of materials for functionally graded parts and issues in forming/casting. Note, not all issues are physical and software can also be streamlined or improved. All of these are less common obstacles, but worthy of documentation. Designers not designing for the use of and workplace acceptance of RM technologies will just take time to resolve.

6. CASE STUDY – LASER AIDED MANUFACTURING PROCESS (LAMP) SYSTEM

The laser aided manufacturing process (LAMP) lab at the University of Missouri-Rolla (UMR) has a 5-axis hybrid laser deposition–removal manufacturing system which has been established by Dr. Liou and other faculty. This system entails UMP integration to build a rapid prototyping/manufacturing infrastructure for research and education at UMR. Integration of this kind was planned specifically to gain sturdy thin wall structures, good surface finish, and complex internal features, which are not possible by a deposition or machining system alone. The goals for LAMP were system design and integration of equipment for the first three years and the subsequent years are for maintenance and process improvement. The LAMP system elements are comprised of commercial CAD and custom layered manufacturing software for process planning, a National Instruments Real-Time (RT) control system, 5-axis CNC motion system, laser cladding process, and CNC machining finishing process. The researchers compared 2.5-D and 3-D layered manufacturing processes and due to the many advantages of 3-D, chose a 5-axis motion system (Ruan et al. 2005). A commercial powder delivery system designed for plasma-spraying processes carries the steel or titanium powder to the substrate via argon. The 1 kW diode laser melts the powder, while the motion system traverses, thereby creating molten tracks in a layer-by-layer fashion as per the tool path generated by the process planning software. To explain the LAMP system from conception to full production, the integration scheme proposed in Section 2 will now be explored.

Step 1: Determine Manufacturing Needs

- Layered manufacturing with metal powder(s)
- Ability to plan and deposit non-uniform layers
- Produce fully dense parts with good microstructure
- Precision machining (material removal)
- Minimize or remove the use of support structures
- Closed-loop control to optimize parameters in real-time
- Motion system that will provide 3-D capabilities for complex geometry

Step 2: Map/Model the Manufacturing Process

The process model of the LAMP system can be seen in Fig. 3, with the additive and subtractive process loop that repeats if necessary. Note the shaded boxes, they are time sinks and contribute to overall error. Furthermore, removing the substrate is not required every time and has been placed in dashed line brackets to indicate this.

Step 3: Label Each UMP

- Laser cladding – Consolidation process (RP additive process)
- CNC machining – Mass-change process (RP subtractive process)

Step 4: Combine UMPs

The shortened process chain of the LAMP system, as compared to Fig. 3, can be seen in Fig. 4. The transportation of the deposited part to the machining center has been eliminated and the surface finish no longer needs to be examined before machining, as it is assumed the part will need finishing. Sharing the motion system by mounting the laser

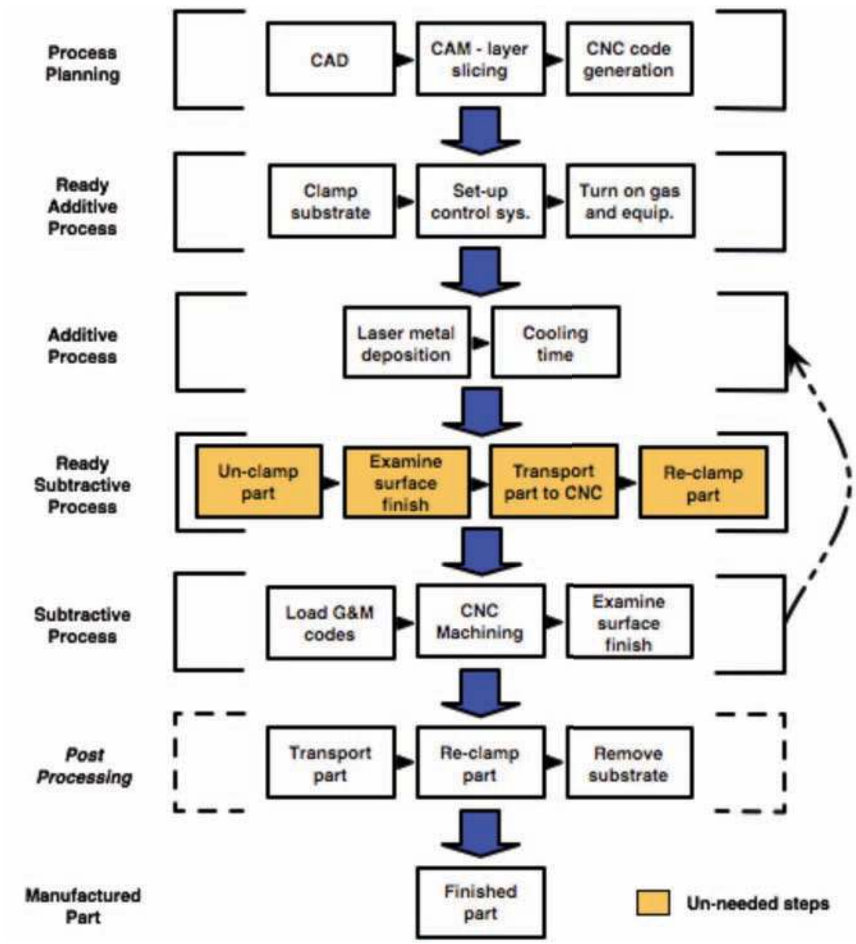

Figure 3: Conceptual Model of LAMP System

cladding head to the Z-axis of the CNC machining center only requires a simple translation matrix to position the part for machining after deposition. If the substrate is essential to the part, then post processing is skipped and the complete manufactured part is now finished.

Step 5: Determine Equipment

Equipment functionality took precedence over other qualities during this step.

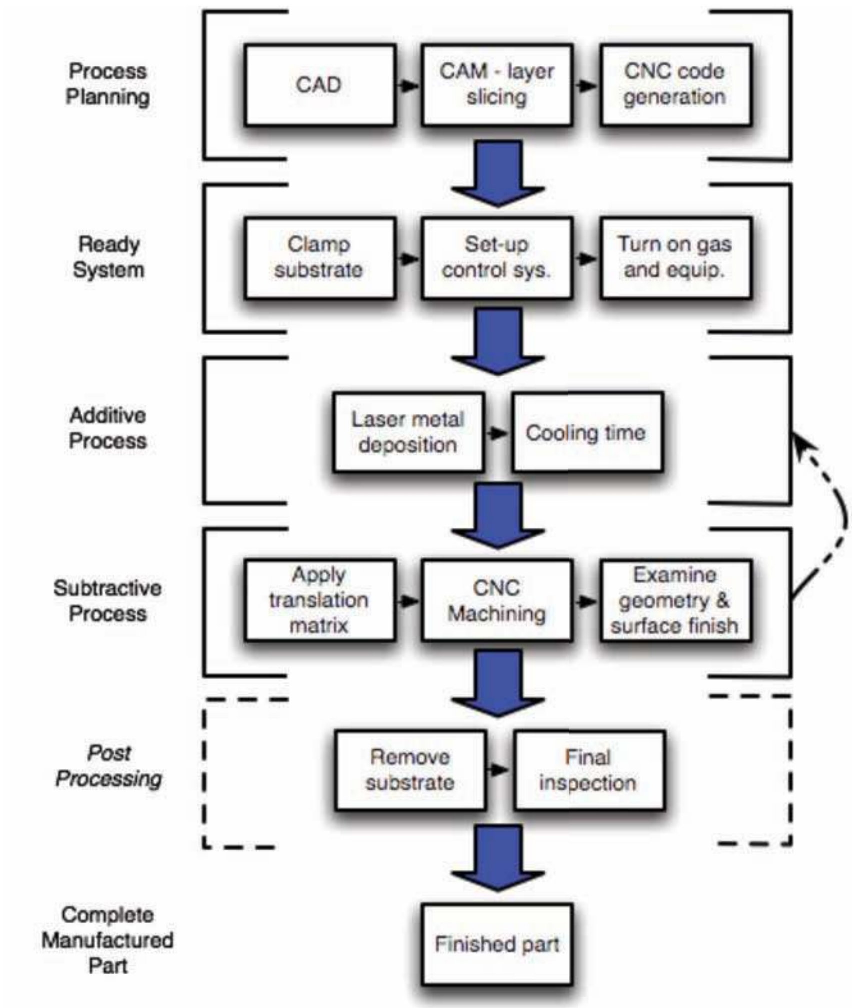

Figure 4: New Conceptual Model of LAMP System with Combined UMPs

The following equipment matched the functionality requirements and was purchased:

- 5-axis CNC Machining Center
- Laser with ≥1 kW of power and chiller
- Laser cladding head with focusing optics
- Tool steel, titanium powder and substrates of the same material
- Powder feeder that provides constant and reliable powder mass flow rate

- Robust RT control system with multiple inputs/outputs
- Cables and wires to interface components with RT control system
- Software that will interface with the RT control system
- Custom software to produce layered tool path
- Commercial software to create 3D objects

Step 6: Build/Retrofit Integrated System

The equipment listed in Step 5 was acquired and combined. The final combined laser cladding and machining UMPs can be seen in Fig. 5. However, the CNC did not come with a pre-defined spot for mounting a laser cladding nozzle or some other type of equipment on the Z-axis of the machine. A platen with precisely tapped holes for the cladding head and additional tapped holes for future equipment or fixtures was mounted to the Z-axis of the machining center. This solution provided great versatility and was later utilized for the mounting of sensors with or without fixtures. Since this type of deposition requires metal powder to be fed into the melt pool, a powder feeder system was also needed to get the LAMP system up and running. The feeder, which needs to be manually loaded, could not be mounted to the CNC and was placed as close as the 16 ft. hose going to the laser cladding nozzle would allow. A problem was encountered here because the cladding nozzle required four powder streams, but the powder feeder provided only one. A LAMP student rapid prototyped a powder distribution piece out of ABS plastic, connected it to one end of four anti-static tubes with the other tube ends connected to the cladding nozzle. The problem of powder distribution was solved with in-house made equipment

Figure 5: Combined UMPs of the LAMP System.

The custom layered manufacturing or slicing software that performs tool path planning and the set-up of the real-time control system took the most amount of build time. The slicing software was a new concept, a modified Voronoi diagram (skeleton), which calculates distance and offset edges or boundaries (Eiamsa-ard et al. 2003). Distance, gradient, and tracing functions were modified to allow more complicated and unconnected known environments for successful implementation in the LAMP system (Eiamsa-ard et al. 2003). The generalized algorithm was robust, but encountered numerical stability problems and took many iterations before the code was usable. Setting up the RT control system required routing cables and wires between the system components that need to be controlled or monitored and the screw terminals on the RT connector blocks, and individual software programs were created to check if the system was wired correctly (Musti 2003). Automating the entire LAMP system was not complete until the tool path motions could be directly sent to the CNC from the RT control system. Due to the age of the CNC machining center communicating with it via the RT control system was challenging. The Direct Numerical Control (DNC) protocol used with the CNC RS-232 port was reverse engineered so that motion commands could be sent simultaneously with laser and powder control commands (Stroble et al. 2006). Just like the software, time and tenacity resolved the ongoing control system obstacles. All components that interface with the RT control system are laid out in Fig. 6.

Step 7: Test Integrated System

While the LAMP system was being constructed, software and hardware were concurrently tested. The custom slicing software created G&M tool path codes for the CNC to perform and were heavily tested as the software was being perfected. Another iteratively tested component was the RT control system. Due to its high customizability and robustness the system had to be fully understood so that the connections and software could be properly made. Testing was extensive. Also, the RT control system inputs and outputs, owned by the UMR lab, are rated for -5 to 5 V or -10 to 10 V only. Thus, static maps correlating 0-10 V with temperature, grams per minute, or watts were created to accurately control or monitor the LAMP system. Retrofitting the CNC with the laser cladding head was simple, but finding the correct process parameters for accurate melt pool consistency and temperature, and layer thickness were not. A design of experiments (DOE) approach was taken to perfect the process parameters and is discussed in depth by (Bhimanapati 2004). Simple geometries were tackled first and by working up to complex geometries as the slicing software was modified, the utilization of all 5 axes was learned and the process perimeters were scientifically verified.

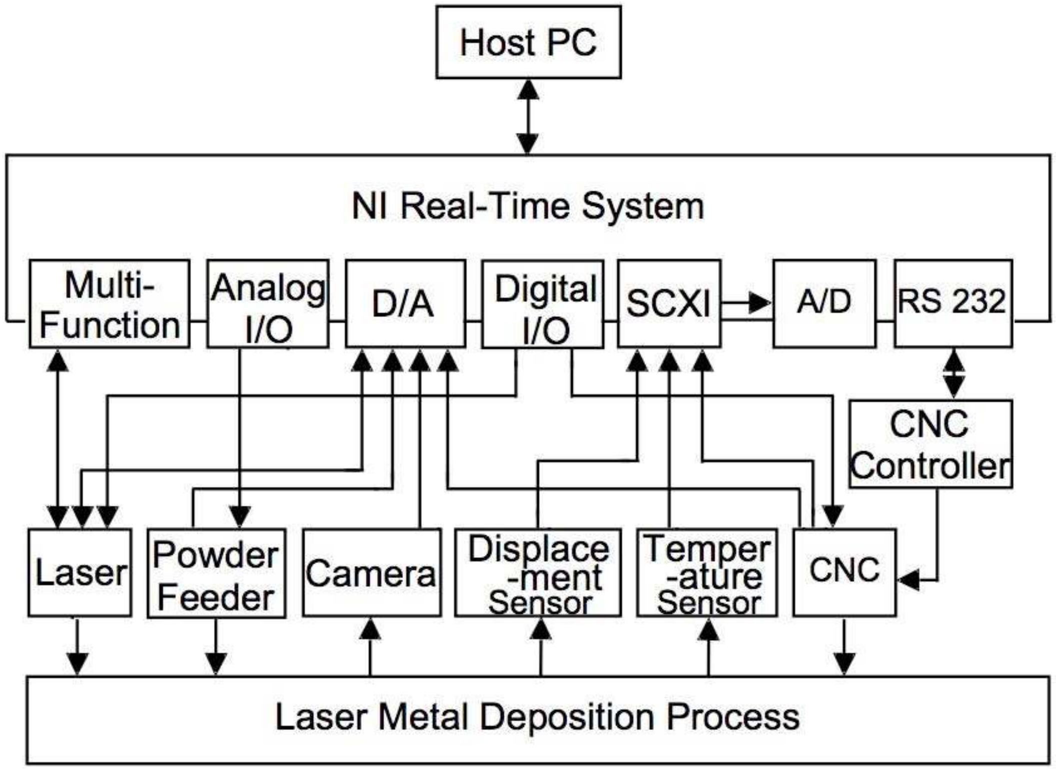

Figure 6: Real-Time Control System Schematic of LAMP System

Step 8: Full Production

The LAMP system is capable of making complex objects and performing part repair. Worn or cracked steel dies for a local company have been successfully repaired using the LAMP system, as shown in Fig. 7 (Ren et al. 2006). Tool steel was deposited completely around the working part of the die and then machined to original shape and size. The custom layered manufacturing software generates codes for 3D tool repair, which can be seen in the center image of Fig. 7 by the curved deposition.

Figure 7: Worn Die that was Repaired (Ren et al. 2006)

Complex and typical 3D shapes can also be created by the LAMP system. A part that was a good challenge is the one shown in Fig. 8. The left image shows the layered tool path, the center shows the expected outcome, and the right image shows the actual after machining. This part was also made of tool steel and the precision machining was the biggest challenge. All five axes were utilized to deposit the shape. Another geometrical accomplishment was building a part with a conformal cooling channel inside of it. This can be seen in Fig. 9. This part was made with tool steel as well.

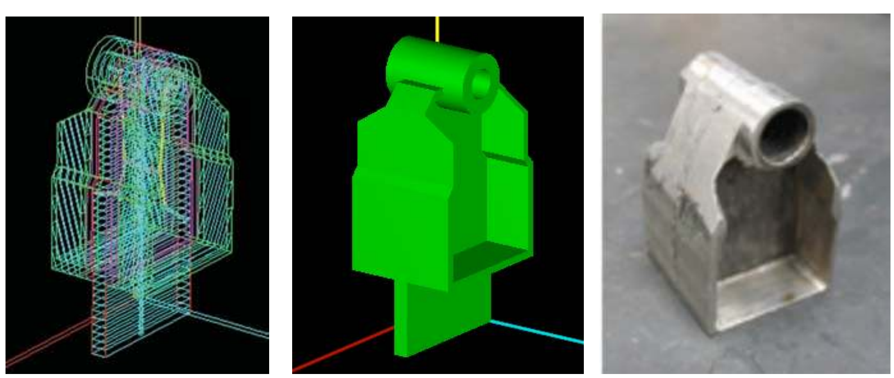

Figure 8: Complex 3D Part

Titanium is the material of choice for aerospace applications (Liou et al. 2005). Many experiments have been run to perfect its deposition process. In Fig. 10, titanium was deposited on the incline to form the rectangular shape and the LAMP system performed very well. There is not any discoloration from oxidation. Also, the dexterity of the LAMP system can be seen, as the LAMP logo was “drawn” on the titanium substrate with titanium powder.

Figure 9: Part with Cooling Channel

Figure 10: Titanium Deposition Sample with LAMP Logo

7. CONCLUSIONS

In this paper, a scheme consisting of eight integration steps and the salient set of five elements of an IFFMS have been presented. It was stressed that the conceptual design phase of the integration scheme was an integral part of achieving the manufacturing goal. Equipment cannot be purchased and expected to work together easily and seamlessly without having a design manner to follow, because design is a concurrent process. The elements of process planning, control system, motion system, UMP, and finishing process were explained to convey their importance and how they should be balanced. All unit manufacturing processes were explained so that a designer could recognize if a system has integration options. Additionally, a combination chart of unit manufacturing processes has been laid out for manufacturing system designers, in efforts to fulfill the need stated by the NRC Unit Manufacturing Process Committee. Furthermore, each step of the integration scheme was discussed to shed light on the construction of an IFFMS.

Obstacles that are typically encountered by IFFMSs were presented and one or more solutions were provided. An example of a laser aided manufacturing process system was provided to explicitly illustrate the use of the integration scheme. Each of the eight steps was walked through to give the reader an idea of how to use the integration scheme to develop an IFFMS. Many images of completed parts with and without complex geometry, part repair, cooling channels and the LAMP logo were shown as examples of full production, fully dense parts ready for use. It was demonstrated that when the five IFFMS elements work together seamlessly, the resulting system achieves the desired manufacturing goal

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PAPER II

AUTOMATION OF A HYBRID MANUFACTURING SYSTEM THROUGH TIGHT INTEGRATION OF SOFTWARE AND SENSOR FEEDBACK

J. K. Stroble[*]*, R. G. Landers*[†]*, F. W. Liou*[*]

[*]Department of Manufacturing Engineering

[†]Department of Mechanical and Aerospace Engineering

University of Missouri-Rolla, Rolla, MO 65409

Email: jksmr6@umr.edu, landersr@umr.edu, liou@umr.edu

ABSTRACT

This paper presents a framework for the automation of the Laser Aided Manufacturing Process (LAMP) lab at the University of Missouri-Rolla. The groundwork for the proposed system involves the integration of the LabVIEW software package and a PXI-8195 real time controller with several sensors and actuators. The incorporation of all key control parameters into one virtual instrument will help achieve the goal of an automated hybrid system. To achieve this goal, a five-phase plan, which will be further discussed in the paper, has been developed. The first phase of this plan, which includes the deposition of a thin walled structure without DNC communication between LabVIEW and the CNC has been achieved, and will be the focus of this paper.

Keywords: Automated control system, design framework, CNC, hybrid system, laser metal deposition

INTRODUCTION

The Laser Aided Manufacturing Process (LAMP) at the University of Missouri-Rolla (UMR) is a hybrid laser metal deposition (LMD) manufacturing system consisting of a laser, powder feeder, and motion system. The laser is used as a heat source while the powder feeder delivers metal powder at a specified rate into the path of the laser beam, thereby creating a melt pool. The laser beam and powder stream are directed vertically, while the substrate moves in three dimensions using the x, y, z, A, and B axes, molten tracks are deposited in layers, which cool rapidly to fabricate a part. Sensors monitor the temperature, layer height, and melt pool geometry in real time via a real time (RT) control system.

The overall goal of the UMR LAMP lab is the complete automation of the hybrid laser aided manufacturing process. To achieve this goal, a five-phase plan to automation has been developed. The five-phase plan involves utilizing sensor feedback to gain overall control of the diode laser, powder feeder, and motion system through a RT control system implemented on a single host computer. Virtual instruments (VI) created within the LabVIEW software package will be used to monitor, drive, and control the hybrid LMD process in real time. The LabVIEW VI will include simulated controllers to compensate for undesired dynamics and noise, thus insuring accurate builds with a stable automated LMD process.

The major focus of this paper will be to discuss the work performed to complete the first phase of the plan, which includes the deposition of a thin walled structure without DNC communication between LabVIEW and the CNC. To demonstrate the implementation of this phase, the paper will look at the equipment, software, and hardware required for control; the results from phase one's implementation; and conclusions drawn from the first phase.

PRIOR WORK

Hybrid manufacturing systems are a conglomeration of many off-the-shelf components that are combined in a modular fashion to achieve a new process. Research was conducted on hybrid systems, individual components, and control applications. While the following research of hybrid systems contains many of the pieces required for an LMD process, there is a general lacking in the areas of total system integration and control.

Two pertinent real-time control applications dealing with laser and vision control are quality control inspection and position control. Real-time vision control for a fabric inspection system was shown to be very successful with dedicated hardware for the vision system being controlled via a Pentium 4 PC [1]. Morgan [2] developed a very reliable way of monitoring high power CO_2 lasers based on the feedback of a light sensor and how to control the focal position of the laser. Both applications mentioned are not associated with LMD, but contain aspects useful in the development of the hybrid system with relation to real-time control.

Under the solid freeform fabrication (SFF) category, two articles by Malone [3,4] demonstrate successful types of positioning systems, deposition tools, and software. However, Malone has shown that small-scale systems are capable of deposition when being controlled by one computer system. Upton [5] has completed research on flexible manufacturing systems (FMS) where the key idea is that co-ordination of workflow is performed by a central control computer. Both authors have laid groundwork in the area of hardware and software integration.

Others at UMR have done research within the LAMP lab or dealing with lasers that is the most relevant to the automation of the LAMP lab. Specifically, Hua [6] has done extensive research in adaptive layer process control with lasers. Additionally, before the LAMP lab went through a major equipment upgrade in the summer of 2005, work went into system integration, experimental analysis, and modeling of the LAMP lab [7,8]. Although many of the components of the LAMP lab were changed, the fundamentals of the aforementioned research remains pertinent to the continued automation of the LAMP lab.

FRAMEWORK

A five-phase framework has been proposed for the automation of a hybrid LMD system, which will be utilized in the UMR LAMP lab. The framework lays out the major steps to achieving automation using real-time control hardware and integration of software with sensor feedback. Detailed steps for implementation of the five-phase framework are elucidated in the Methodology section. The parameters needed for successful framework completion are further discussed in the Parameters and Equipment for System Integration and Automation section.

Phase 1: The first phase of automating the hybrid LMD process is to deposit a thin wall structure without DNC communications between LabVIEW and the CNC. Phase one demonstrates the ability to command the diode laser and powder feeder by the

RT system and to simultaneously fabricate a part when a tool path is loaded on the CNC from another source.

Phase 2: Phase 2 of the framework is similar to the first. A thin wall structure is deposited with DNC communication of the toolpath to the CNC from the VI running the laser and powder feeder. Depending on the type of CNC used and amount of on-board memory, drip-feeding of the tool path to the CNC may be required to fabricate the thin wall structure.

Phase 3: Building upon the second phase, the third phase incorporates feedback from an intelligent vision system which monitors melt pool geometry. During deposition, the melt pool is monitored for elliptical geometry because as the substrate traverses, the round pool elongates. A feedback controller should be implemented that can interpret geometric feedback and compare it to the desired output. Once the melt pool leaves the allowed dimensions for the chosen laser power and powder mass flow rate, the deposition process reaches a warning mode. If the vision system continues to report poor melt pool geometry for more than the allotted time, the LMD process faults and is shut down immediately.

Phase 4: The fourth phase includes more sensor feedback by monitoring the temperature of the melt pool by a non-contact optical sensor. Due to the high priority of creating quality depositions, regulating the temperature of the melt pool is critical to achieving the desired microstructure. Modify the phase 3 controller to process additional data and simultaneously determine if the feedback is desirable. Once the measured temperature leaves the allowed range for the chosen laser power and powder mass flow rate, the deposition process reaches a warning mode. If the temperature sensor continues to report an out of range temperature for more than the allotted time, the LMD process faults and is shut down immediately.

Phase 5: The fifth phase incorporates the final sensor feedback, height of deposited layers, needed to complete the hybrid LMD system framework for automation. Incorporation of the laser displacement sensor feedback is an offline process that requires the deposition to pause so the sensor can scan the deposited structure, attain data, and display the data in real time. Modify the phase 4 controller to automatically process the offline feedback, and provide the option for an operator to decide if the data is acceptable. If the data is acceptable, the LMD process will continue, otherwise it will be shut down.

METHODOLOGY

Development of the automation program to command and monitor a hybrid LMD system is comprised of several smaller tasks that build upon each other. The details needed to follow the proposed framework are contained within this section and describe the underlying work necessary for success. Completing the steps in sequence is critical when using this methodology.

Step 1: Test all LMD system devices for compatibility with the RT system hardware. Make necessary modifications to the devices as needed; such as building a special cable.

Step 2: Use the software package online diagnostic program to test if the software can accurately communicate with the devices. If using LabVIEW, the program

Measurement and Automation Explorer (MAX) is used for online diagnostic tests [9].

Step 3: Create a basic VI to monitor the input and output of each device individually. The VI should contain at least a graph or chart that displays the output; fields for input parameters such as voltage, sampling rate, input channel, encoding type, ect., and a field to specify or monitor the save file path where the collected data will be stored.

Step 4: Perform open-loop step tests using the VI's created in Step 3 and record data to be analyzed. With a suitable mathematical software package, analyze collected data, and compare it to the predicted outcome. Look for system dynamics that will require additional modeling for compensation. Look for delays in the output that will inevitably affect the overall system performance.

Step 5: If emulation is necessary, create mathematical models for the devices that exhibit significant dynamics to understand how to remove their disturbance from the overall system. Add code to the VIs created in Step 4 mimicking the mathematical models. Repeat Step 4. If emulation is not needed, then skip Step 5.

Step 6: For devices that only need to be monitored, new VIs will not be required in this step. Again, execute Step 4 using the VIs from Step 5 if emulation was used, until desired results are achieved. Develop an adequate controller that will regulate the output signals sent by the RT system to the controlled devices of the LMD process. A new VI should be created for each device and include the controller code. Execute Step 4 until the open-loop tests provide desirable results. Next, update the new VIs to incorporate the feedback from monitored devices and perform closed-loop tests until desirable results are achieved.

PARAMETERS AND EQUIPMENT FOR SYSTEM INTEGRATION AND AUTOMATION

System integration of software and sensor feedback for an automated system is typically accomplished through a real-time control system [10]. Communication and automation play a major role in the automation scheme of the RT control system for the hybrid LMD process. Therefore, a fast sampling controller, network card, analog and digital I/O ports, serial ports, hardware timers and counters, D/A converters, A/D converters, and hardware filters are some of the key aspects of a reliable RT control system as laid out in Fig. 1. Conversely, a robust software package is required for overall tight system integration. LabVIEW, the software chosen for the LAMP lab, is a powerful software package developed by National Instruments. The LabVIEW software package is a robust and expandable software package for design, control, and testing [9]. Development of VI's, component control, and monitoring for the LAMP lab are completed as described in the methodology section. Figure 1 shows all the device inputs and outputs of the LAMP lab hybrid LMD process.

The advantages to implementing an integrated system are three-fold. First, the hybrid LMD process can be made safer by becoming an automated process and removing people from directly interacting with the components and laser. Second, the options for control and feedback are endless and versatile. There are no limits on the number of VIs that can be created with the LabVIEW software package, so numerous programs can be

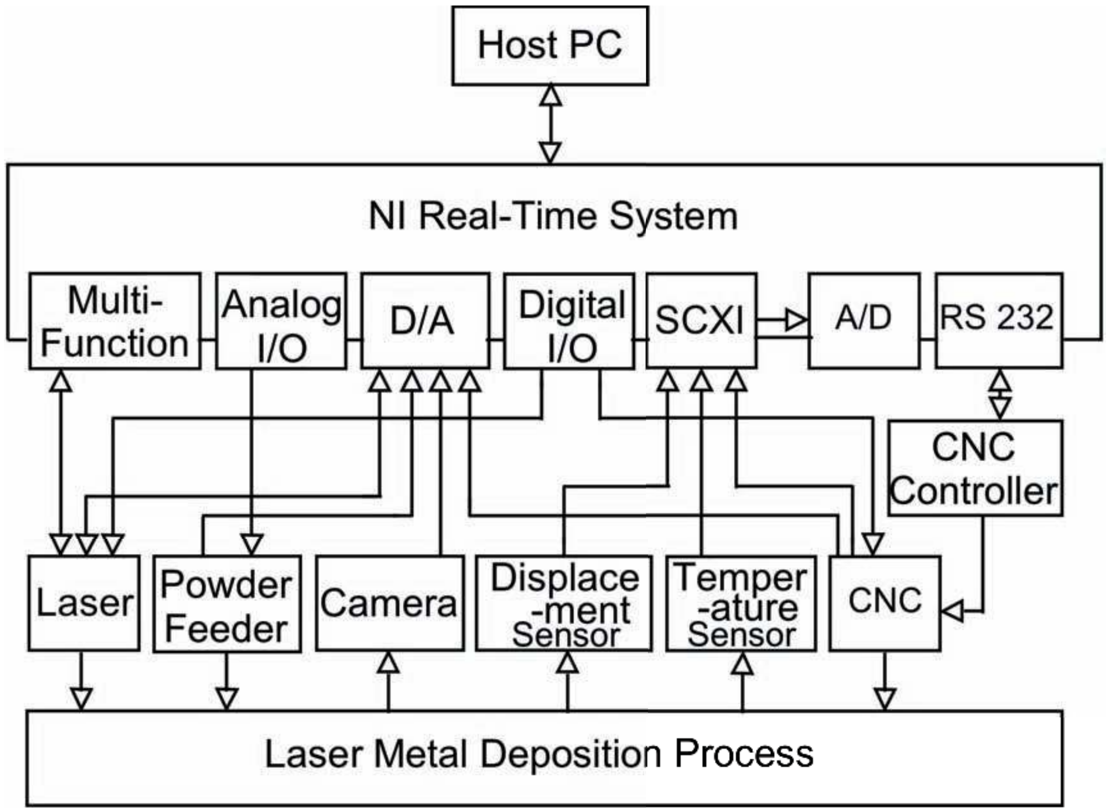

Figure 1: Block Diagram of LAMP Automation System

developed and executed on the RT system or stored for later use. Thus, the hybrid LMD system is only limited by the hardware, which includes the I/O and CPU of the RT system. Third is repeatability leading to better quality control. With full automation, the hybrid LMD process will fabricate parts that have predictable and desirable characteristics more frequently.

Some process parameters are not appropriate for real time control and should be held constant during the process of fabrication. The spot diameter provides the clad width and is determined by the focal length of the laser lens and the standoff distance. Thus, repositioning the z-axis can only change the spot diameter. This would require G codes to be sent to the CNC. Changes to the G and M codes sent to the CNC cannot be completed in real time because there is a delay when waiting for the last line of code in a program to be executed. Another factor is that the setup of the powder feeder nozzle must ensure that the metal powder converges at the melt pool in a diameter roughly the size of the spot diameter. Altering the spot diameter would thus require an adjustment to the powder feeder nozzle, which cannot be done in-process. The table velocity is also not a candidate for real-time control. Only after a tool path program has been completed can the table velocity be changed because the whole program is sent to the CNC at once. Similarly, the tool path must also be set before the process begins. The two process variables that can be used for real time control are laser power and powder mass flow rate since they can be controlled independently of the other process parameters and the CNC.

Key parameters for system integration are the ones that can be manipulated in real-time to induce a change in the final product or monitored for use with a feedback control scheme. By controlling and monitoring the key parameters, the quality of fabrication will increase and be repeatable. An overview of the parameters is given next along with how the device was affected by the steps presented in the methodology section.

The main difficulty involved with controlling the powder mass flow rate in process is the natural delay that occurs between the control signal and the actual output. Powder mass flow rate is controlled by a command voltage, which regulates the rotational speed of the powder delivery shaft. The powder must then traverse the delivery system before entering the melt pool thereby creating a delay between the effective mass flow rate and the desired mass flow rate. Argon is used as the carrier gas for transporting the powder from the powder feeder to the laser collimator at a pressure of 40 psi. Also, a special cable was made to make the powder feeder mass flow rate (gpm) controllable by the RT system. Other considerations include the location of where the powder stream converges to the location of the melt pool and preheating the powder to remove moisture. Preheating improves flow and helps minimize porosity in the finished part.

Controlling the diode laser power by a command voltage was achieved by way of a special cable that connected the laser to the RT control system. The only delay is the 0.5 ms response time of the laser [11]. The difficulty with controlling the laser power is determining what the desired laser power should be based upon the desired clad dimensions. Increasing the laser power increases the size of the melt pool and could increase the size of the deposition height if enough powder is present. The laser power must also be within a certain effective range for a given material since the final mechanical properties of the part, such as porosity, density, and microstructure, are closely related to laser power through melt pool temperature and solidification time. Laser power must also be large enough to induce melting in the substrate, but must also be below the point where dilution causes poor solidification.

Real time monitoring of the melt pool length and width are important to maintain the dimensional accuracy during laser deposition [8]. Melt pool geometry is directly affected by the laser power and powder mass flow rate. Dilution of the melt pool will result in poor cladding and produce unacceptable part quality. In order to monitor the melt pool geometry, a side bracket attached to the collimator emulating an axial mount with the use of two dichromic mirrors allows for a CMOS camera to acquire melt pool images during deposition in real-time. The length and width of the melt pool are extracted using an image-processing algorithm in real-time and used for feedback control during the last three phases of the framework.

Layer height must be determined to calculate the number of layers that need to be run to minimize the use of raw material [8]. A non-contact laser displacement sensor is used to measure the layer height after an individual layer or a given number of layers have been deposited. Height is affected equally by the powder mass flow rate and the laser power. A higher laser power combined with more powder, leads to a bigger clad. In order to measure the height with the RT system reliably, a hardware filter was installed into the RT control system to alleviate most of the noise in the signal. The same is true for the temperature sensor, but with the addition of resistors to reduce the voltage output.

Melt pool temperature is monitored continuously, in real time, using a dual-wavelength non-contact temperature sensor. If the temperature is too low, then the powder injected into the molten pool will not melt. Moreover, if the temperature is too high, it risks the danger of melting the previous layers too much or causing damage to the work piece [8]. The sensor measures the peak temperature of the melt pool formed during laser deposition and is used for feedback control during the last three phases of the framework.

Direct Numerical Control (DNC) is a feature of the CNC machine that allows for a host PC with an RS-232 port to communicate with the CNC remotely. The 64Kb of memory local to the CNC is used when downloading a program at 9600 baud into the CNC memory for execution [12]. Since the CNC memory size is very small compared to a complete tool path program, the 64Kb of memory can then be used as a buffer for the program and frequently replenished by the remote PC until the full program has been loaded into memory and executed. This is also known as “drip feeding.” The buffer fills after a few lines of code have been executed and continues to stay full at 256 lines of code until the last line of the program has been sent. However, the most important advantage to DNC is the way it handles large program files by drip feeding them to the CNC smoothly until the program is finished. This allows for large tool path programs to be automatically executed. Using the diagnostic software, it was discovered the CNC needed a special command to initiate DNC capabilities thus allowing for the phase two progress to begin.

RESULTS

Phase one of the LAMP lab framework has been completed and is demonstrated by the preliminary results shown in Figure 2. The thin wall structure was deposited semi-automatically, which means that the host PC communicating to the RT system commanding the laser power and powder mass flow rate did not drip feed the tool path to the CNC. Another computer currently dedicated to performing DNC was used to send the tool path program to the CNC. Additionally, the main VI did not incorporate feedback control when the preliminary results were attained. The user of the main VI could control the powder feeder and laser voltage commands, and monitor and record their respective feedback signals. The integration of the software with the hardware was evident when the laser and powder feeder responded to the command signals without any complications, noticeable delay, or the loss of data samples. Given the robust nature of

LabVIEW, the preliminary deposition task was simple to implement and was performed effortlessly by the RT system.

As one can see from Figure 2, the deposition was very clean and had nice quality on the outside. The first deposition (bottom) warmed the substrate, subsequently allowing the second deposition (top) to have better dimensional accuracy. Microstructure and porosity are still yet to be determined for the samples in Figure 2. To achieve such results, a powder mass flow rate of 8.25 gpm and a laser power of 700 W were used, which corresponds to a command voltage of 1.3 V and 6 V, respectfully.

Figure 2: Semi-Automatic Deposition of a 20 Layer Thin Wall Structure

The correct command voltage for the laser and powder feeder were determined experimentally through open-loop step tests. Table 1 provides the steady state results of gpm and rpm for command voltages between 1–2 V, in 0.1 V increments. The rpm was recorded by the RT system at a sampling rate of 1000 Hz, and the caught grams of powder were measured on a scale. A VI was created to automatically send a command voltage to the powder feeder for one minute, shut off the powder flow by sending 0 V, and then stop the program. During that minute, powder was captured in a glass jar at the end of the nozzle and weighed on a scale for 30 seconds to allow enough time for an approximate reading of total grams of powder, as recorded in Table 1.

Consequently, the four tests were averaged and checked for acceptable standard deviation. The results were suitable and can be found in Table 2. The data in Table 2

Table 1: Results of Powder Mass Flow Rate Open Loop Tests

Command Voltage (V)	Recorded gpm (approx.)	RPM	Recorded gpm (approx.)	RPM	Recorded gpm (approx.)	RPM	Recorded gpm (approx.)	RPM
	test 1		test 2		test 3		test 4	
1.00	4.90	0.5047	4.60	0.499	4.80	0.5024	4.73	0.5013
1.10	6.02	0.6548	5.80	0.6497	5.90	0.6575	5.92	0.6572
1.20	7.15	0.811	7.13	0.8067	7.14	0.8089	7.19	0.8071
1.30	8.42	0.9564	8.33	0.9562	8.23	0.9557	8.25	0.9572
1.40	9.50	1.115	9.37	1.11	9.40	1.11	9.36	1.11
1.50	10.40	1.263	10.38	1.264	10.40	1.263	10.35	1.262
1.60	11.48	1.422	11.52	1.422	11.39	1.425	11.30	1.427
1.70	12.52	1.578	12.22	1.58	12.30	1.581	12.23	1.58
1.80	13.00	1.737	13.13	1.739	13.00	1.742	13.13	1.727
1.90	14.35	1.88	14.46	1.881	14.29	1.884	14.25	1.882
2.00	15.14	2.044	15.03	2.047	15.41	2.047	15.84	2.047

Table 2: Averages and Standard Deviations for Data in Table 1

Command Voltage (V)	GPM Avg.	RPM Avg.	GPM Std. Dev.	RPM Std. Dev.
1.00	4.76	0.5019	0.13	0.0024
1.10	5.91	0.6548	0.09	0.0036
1.20	7.15	0.8084	0.03	0.0020
1.30	8.31	0.9564	0.09	0.0006
1.40	9.41	1.1113	0.06	0.0025
1.50	10.38	1.2630	0.02	0.0008
1.60	11.42	1.4240	0.10	0.0024
1.70	12.32	1.5798	0.14	0.0013
1.80	13.07	1.7363	0.08	0.0065
1.90	14.34	1.8818	0.09	0.0017
2.00	15.36	2.0463	0.36	0.0024

provides a reliable guide for the user when programming a VI for control, because the gpm has been correlated to command voltage. Figure 3 shows the relationship between command voltage and the powder mass flow rate with a calculated slope of 10.4 when analyzed using the least squares method. Pleasingly, the correlation coefficient was found to be 0.999. Deviation within the rpm test data is negligible in most cases, but the gpm deviation was large for voltages of 1.00, 1.60, 1.70, and 2.00. It is hypothesized that fluctuations between gpm test results are mainly caused by the powder wheel mechanism consisting of a cam and flexible follower within the powder feeder. The position where the powder wheel starts and stops during each test has a great impact on the amount of powder released by the mechanism, because each cycle of the powder wheel is not identical. Large deviations were also partially due to measuring the grams by hand with a scale and recording the value that was displayed most frequently within the 30 seconds

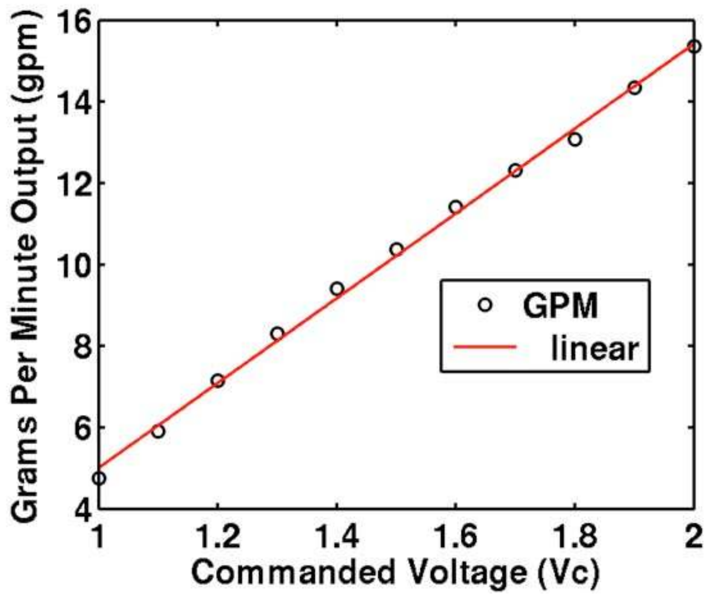

Figure 3: GPM Test Results of the Remotely Commanded Powder Feeder

the jar rested on the scale. Moreover, the type of distribution system installed before the collimator splits the main powder stream into four, and can become clogged, statically charged, or leak carrier gas, which can deteriorate powder delivery performance significantly.

Figure 4 relates the average command voltage to the rpm. When the rpm data was analyzed using the least squares method, the slope was found to be 1.5. The correlation coefficient was found to be exactly 1.000 indicating a nice linear relationship as shown in Figure 4. Finally, the gpm and rpm test results were correlated in Figure 5 and the slope was found to be 6.7 by the least squares method. The results in Figure 5 were greatly affected due to the powder feeder mechanism and powder distribution system as

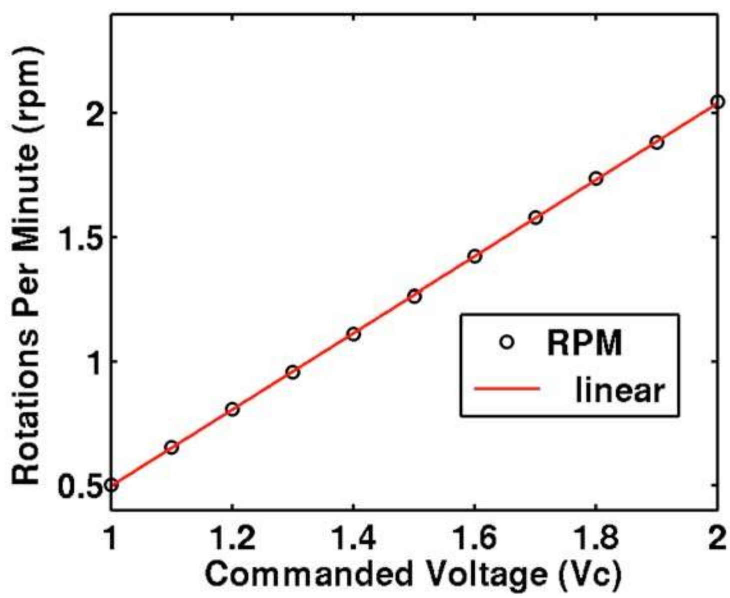

Figure 4: RPM Test Results of the Remotely Commanded Powder Feeder

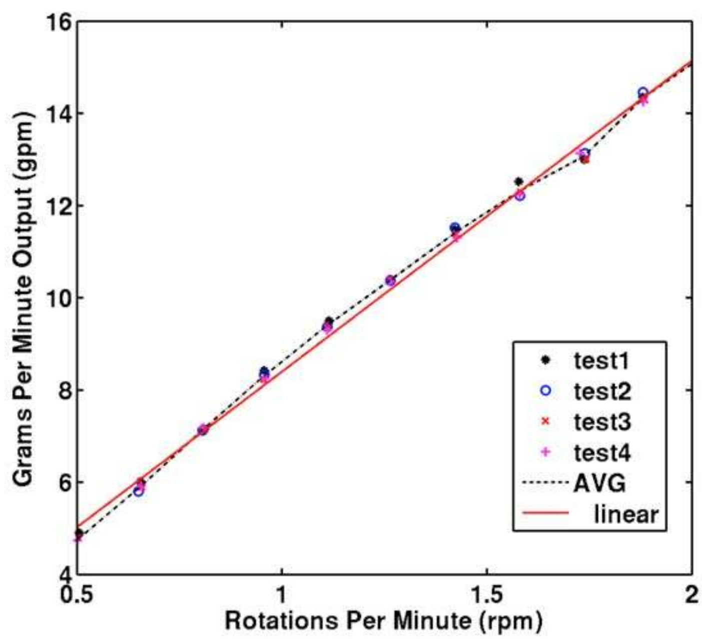

Figure 5: GPM Results Compared to RPM Results of the Remotely Commanded Powder Feeder

previously mentioned. However, the relationship between the rpm and gpm is approximately linear with a calculated correlation coefficient of 0.998. Deposition test results have proven the collected data in the voltage range of 1-2 V to be reliable for use with the LMD process.

Correlation between the commanded voltage and output wattage to the substrate was conducted using a Coherent Power Meter with the water-cooled LM5000 sensor head, rated for 5 kW. The sensor head was placed below the collimator at a standoff distance of 14.478 mm (0.57 in), and a voltage was commanded in 1 V increments to the laser by the laser VI. The bolded columns of Table 3 list the given documentation of the diode laser. The recorded measurements from the power meter tests at the substrate are labeled Pm Test, and the data standard deviation are in Table 3. Correlation between the provided documentation and the power measured at the substrate is in Figure 6. By the least squares method, the slope for the given information was found to be 167.00, and the

Table 3: Laser Power Meter Test Results

Vc (V)	Pm Test 1 (W)	Pm Test 2 (W)	Amps Displayed (A)	Pm Test 3 (W)	Pm Test 4 (W)	Amps Displayed (A)	Pm Std. Dev.	**Nuvonyx Displayed Amps (A)**	**Nuvonyx Output Power (W)**
1	0	0	5	0	0	5	0	**10**	**57**
2	17	17	11	17	17	11	0	**15**	**225**
3	220	220	16	220	220	16	0	**20**	**399**
4	380	380	21.5	370	370	21.5	5.7735	**25**	**574**
5	560	550	27	520	510	27	23.8048	**30**	**737**
6	700	700	32.5	660	650	32.5	26.2996	**35**	**884**
7	820	840	38.5	800	770	38.5	29.8608	**40**	**1014**
8	940	930	43.5	900	890	43.5	23.8048	**45**	**1124**
9	1030	1020	49	1010	990	49.5	17.0783		
10	1050	1020	49.5	1050	1020	49.5	17.3205		

slope for the measured information was found to be 128.00. It was calculated that the laser output correlation coefficient of the Pm Test average was 0.990, which is demonstrated by the large deviations at 1 and 10 V, where as, the given information correlation coefficient was 0.995. Due to losses in heat and the fiber optic medium, the power meter displayed a lower output wattage than what was to be expected as per the diode laser documentation. Furthermore, at the lower range of the voltage input, the output wattage is very close to the provided documentation. It is only at higher command voltages that the laser does not perform as expected.

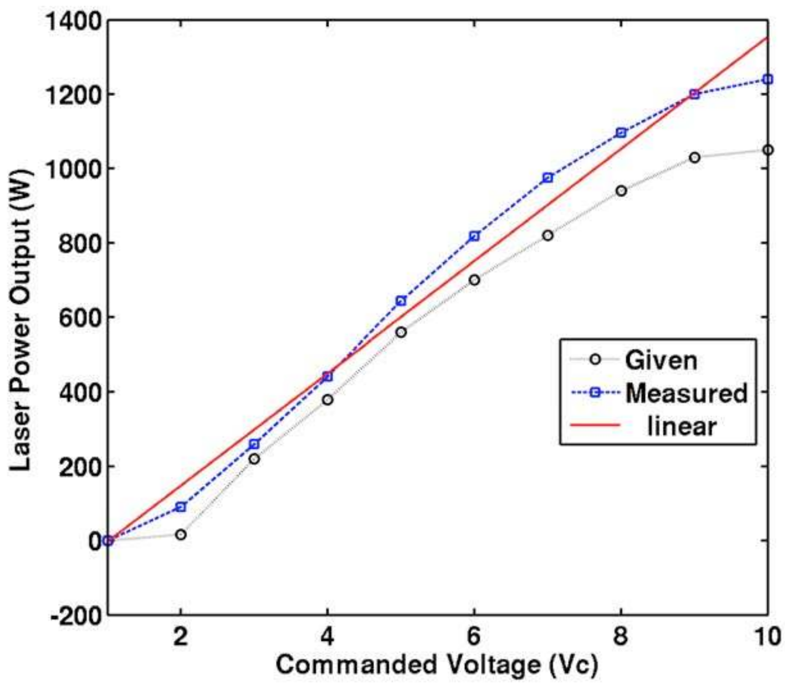

Figure 6: Comparison of Actual Laser Output to Given Laser Documentation

CONCLUSIONS AND FUTURE WORK

The framework for accomplishing the goal of automating the UMR hybrid LMD system has been presented. By following the presented methodology for integrating hardware and software, individual manipulation and monitoring of laboratory components has been achieved successfully. Methodology steps one and two proved to be very helpful in alleviating many unseen problems that did not seem evident in the beginning. Mainly, the temperature sensor needed to be modified for use with the RT system. Preliminary results were demonstrated through deposition samples as shown in Figure 2. The collected data presented in the results section demonstrates that phase one of the framework was successfully completed, because the main VI was only given control parameters and did not rely on feedback. Integration of the software package, RT system, and LMD components was confirmed to be imperative and achievable for the success of full automation.

The future work needed for completing the framework is to actively send information from the RT system directly to the CNC by way of RS232 communication to complete the DNC requirement of phase two. Once the DNC is completed, the last three phases will incorporate the feedback of the monitoring devices and how they interact with the overall system. A robust controller will need to be developed that can handle the feedback from three devices adequately. Real-time processing of feedback from devices simultaneously and driving the computed error signal to a minimum will be the capabilities of the controller. After feedback control is in working order, fault conditions will be added to increase the quality of deposited parts created in the LAMP lab.

ACKNOWLEDGMENTS

This research was supported by the National Science Foundation Grant Number DMI-9871185, the grant from the U.S. Air Force Research Laboratory contract # FA8650-04-C-5704, and UMR Intelligent Systems Center. Special thanks to Robert Nagel for his assistance with this paper. Their support is greatly appreciated.

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SECTION

2. FURTHER DEVELOPMENT OF THE AUTOMATED CONTROL SYSTEM FRAMEWORK

The importance of a control system within an integrated manufacturing system was established in Paper I and discussed in detail in Paper II. In this section, Paper II is expanded upon to document its further development. The automated control system framework consisting of five phases was introduced in Paper II along with the first phase results. Note: due to the pressing importance of process temperature, the framework proposed in Paper II has been updated, *Phase 4* has been changed to *Phase 3* and *Phase 3* has now been changed to *Phase 4*. (See Fig.2.1) This switch is advantageous because a melt pool image would not provide temperature information, but prior temperature information would allow the correlation of temperature to melt pool size. In this section, the results and current status of the second, third, and fourth phase of the framework are presented in separate subsections. Furthermore, to complete all five phases a future work subsection is provided.

2.1 PHASE 2 – ESTABLISH DIRECT NUMERICAL CONTROL (DNC) COMMUNICATION

An integral part of a robust control system is that it can communicate with all devices reliably. Within the Laser Aided Manufacturing Process (LAMP) lab, the control system is required to communicate with six devices at any given time as shown in Fig. 1 of Paper II. The laser, powder feeder, and CNC are receiving commands, where as, the camera, temperature sensor, and displacement sensor are sending feedback to the

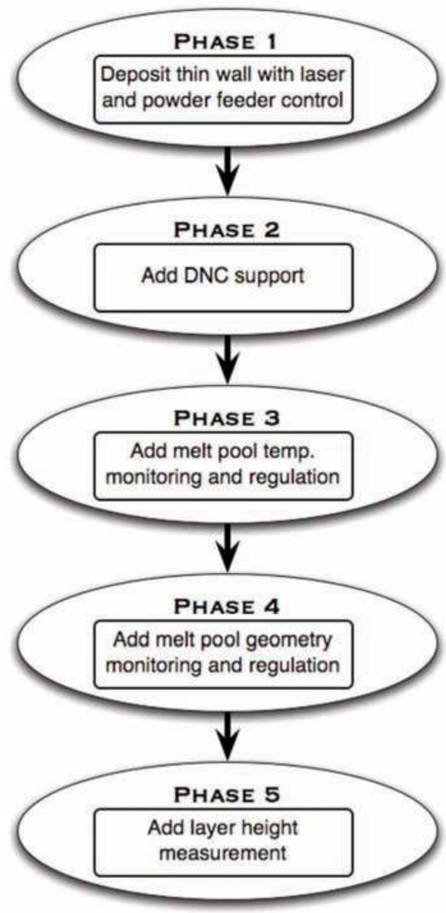

Figure 2.1: Updated Framework for an Automated Control System

controller. In order to completely automate the LAMP system a part program containing commands for the laser, powder feeder, motion system, and machining needs to be loaded by the control system, parsed through, and disseminated to all components so they are all synchronized. The complete control process is visually explained in Fig. 2.2. Starting at the user level, the PC handles the CAD file, process planning and the part program. This information is sent to the control system for parsing and dissemination to the controllers. Simultaneously, the sensors are reading data and sending feedback to the control system. The feedback is utilized during the deposition process if the feedback signal line type is shown leaving the device, otherwise the feedback signal is simply displayed to the user and recorded for analysis. The control signal type that is sent to each physical device is the italicized word under each controller box in Fig. 2.2. A feedback loop is established between the sensors and physical devices. Sensors are measuring and sending feedback in real-time to regulate the control signals in real-time. Presently, the temperature and machine vision sensors are not implemented in the feedback loop, and the displacement sensor is not in commission.

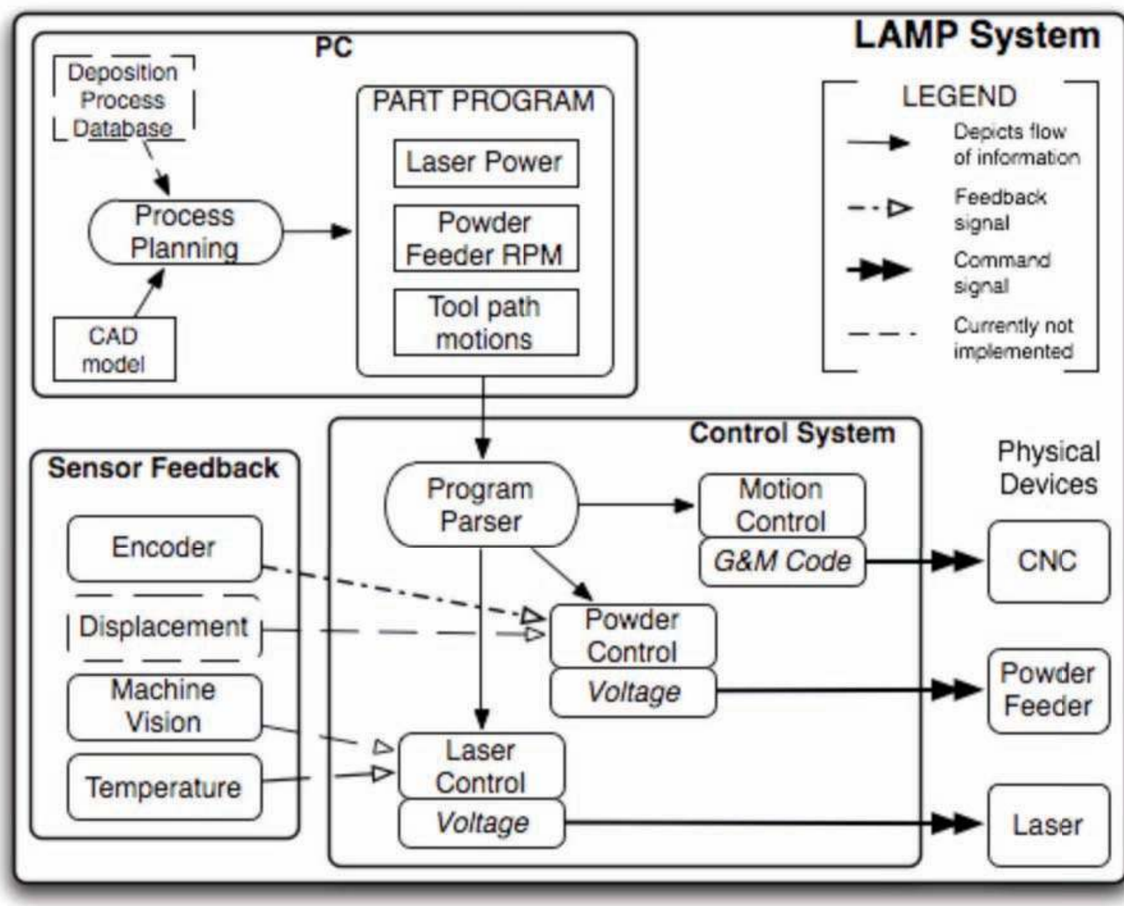

Figure 2.2: Complete LAMP System Communication Layout

The part program is a text file with a column of data for each component, which is sent by the PC in Fig. 2.2 to the parsing program. The column for the laser and powder feeder are desired wattages and grams per minute, respectively. The tool path motions column is sent to the CNC and is comprised of G&M codes along with the protocol that establishes RS-232 communications. In the case of the LAMP system, motion and machining commands are both G&M codes and will not have separate columns within the part program. Thus, it can be understood that communication with the CNC is of utmost importance for complete automation of the LAMP system to occur.

Communications were established with the Fadal CNC machining center via RS-232, also known as serial. However, the CNC did not have the capability to be remotely controlled by anything other than a PC running the Assist software package that came with the CNC. Reverse engineering was utilized to understand the CNC's RS-232 protocol. Once that was determined, a simple RS-232 communication program was written to load a tab delimited text file and send the appropriate information to the CNC; handshaking was established between the CNC and the control system to continuously fill the buffer with G&M codes. Every time a program is sent to the CNC, by any method, the CNC does not execute the tool path motions until the user presses start on the operator interface, which includes a keyboard, screen, knobs and switches. Remotely executing the "start" command was also learned, but not implemented to insure the users safety. When a part program is loaded by the control system, the press of the start key at the CNC initiates the execution of all control system commands. However, this approach revealed that the laser and powder feeder were in sync with each other, but not with the tool path motions. Therefore, a relay was installed to signal that a line of G&M code was executed, which is monitored to synchronize the execution of all part program commands. Simple part programs that build thin walls, such as those shown in the Results Section of Paper II (for *Phase 1*) have been successfully sent and built and can be seen in Fig. 2.3. Additionally, a more complicated hybrid tool path was sent and built to test the robustness of DNC communication. Figure 2.4 shows the successful result of the hybrid tool path trial, which has eight layers (>600 lines of code) and filled the buffer multiple times during deposition.

Figure 2.3: Thin Walls Built by Computer Control

Laser and powder feeder communications were established for phase one, which consisted of sending a 0-10 V signal to either device directly from the control system. This was established by connecting the remote input lines on the two devices to the analog out lines on the control system. Lastly, establishing feedback communications are quite simple with the National Instruments Real-Time Control System. The signal sent

Figure 2.4: Hybrid Tool Path Part Built by Computer Control

by the feedback device is converted to voltage, if it is not already, and the analog signal is monitored. All feedback communications are established.

2.2 PHASE 3 – ADD TEMPERATURE FEEDBACK

Temperature is a critical factor within a laser metal deposition process, as elucidated in Paper II. The desired melt pool temperature ensures expected microstructure, bonding between layers, and constant melt pool shape. These important attributes can be achieved by understanding each process parameter in detail and how it affects the end result. Once the process parameters in Fig. 2.5 have been explored by a design of experiments (DOE) method and correlated, they can be used intelligently to achieve desired results. They can be further applied to develop a closed-loop controller that will automatically adjust process inputs to maintain chosen process parameters.

Additionally, for both in and out-of-control processes, the feedback will be used to signal if the process is unstable and warn when becoming unstable. However, due to

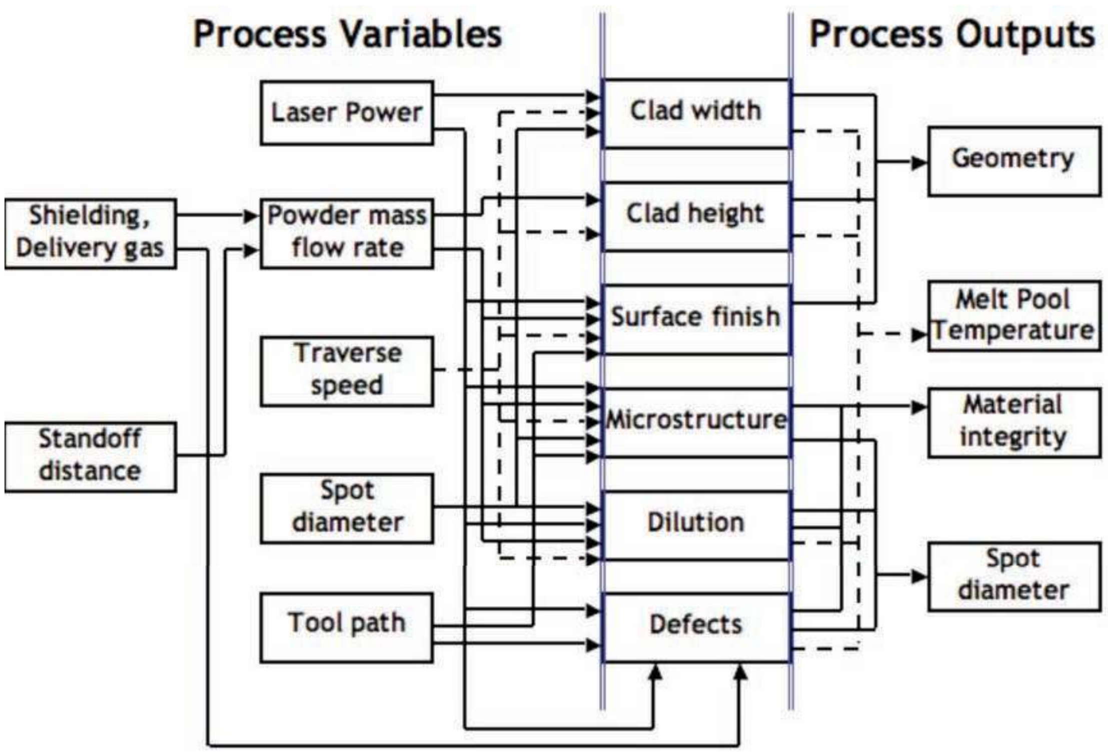

Figure 2.5: LAMP Process Parameters

the complexity of the laser deposition process it needed to be analyzed and deemed statistically in or out-of-control based on temperature, before temperature feedback could be used as a variable for closed-loop control. An in-control process does not need to utilize temperature feedback for a closed-loop system, where as, an out-of-control process needs to be controlled by closed-loop methods to produce desired results. A reliable method for proving whether a process is in or out-of-control is Statistical Process Control (SPC) (Montgomery 2005).

Phase 3 consists of multiple parts:

- Acquire temperature sensor

- Set-up, mount and calibrate sensor
- Run preliminary tests to ensure proper functionality
- Take several data samples to understand the temperature of the LAMP
- Analyze data samples using SPC methods
- Determine whether the LAMP system is in or out-of-control
- Establish a feedback loop to control LAMP if out-of-control
- Establish a warning system with temperature feedback

The first step to taking measurements was to acquire a reliable, fast and accurate temperature sensor that is compatible with a diode laser. A Mikron MI-GA5-LO non-contact, fiber-optic, infrared temperature sensor was chosen for the LAMP system. It was installed onto the Z-axis of the CNC with a custom, adjustable fixture. The set-up for data acquisition was at an angle of 42°, 180 mm from the melt pool and sampling every 2 ms. Furthermore, the sensor is functioning as expected and communicates flawlessly with the RT control system. Preliminary tests, thin wall depositions, have been run for both H13 tool steel and Ti-64. At-a-glance, the tests have shown that the melting temperature of both materials is within the expected range. The current status of *Phase 3* is taking several data samples to understand the temperature of the LAMP system. All other steps are excellent future work.

2.3 PHASE 4 – ADD VISION SYSTEM FEEDBACK

The vision system would be implemented to monitor the ellipsoidal melt pool geometry, length and width and rotation, during deposition to ensure the dilution of the melt pool is correct for the chosen process parameters. A large melt pool signals that the laser power and temperature could be too high, where as, a small melt pool signals that the powder mass flow rate is too high for the current laser power and is not fully melting. Therefore, the vision system is another way to monitor the laser power and powder mass flow rate simultaneously, and could be implemented as a backup method to check against the temperature sensor and encoder feedback signals. If the signals are different then one or both of the other sensors could be malfunctioning, incorrectly positioned, or off-line.

Phase 4 consists of multiple parts:

- Acquire vision sensor
- Set-up, mount and calibrate sensor
- Run preliminary tests to ensure proper functionality
- Take several data samples to understand the melt pool geometry of the LAMP
- Correlate melt pool images with temperature
- Establish a warning system with melt pool geometry feedback
- Establish a feedback loop to aid in the control of the LAMP if out-of-control

There was no need to acquire a vision sensor in this case, a Fastcom iMVS-155 CMOS intelligent machine vision system was already employed by the LAMP lab. It can image between the wavelengths of 400 and 1000 nm. The sensor was utilized with the old LAMP system (Nd:YAG laser and gravity fed powder feeder) configuration and was re-calibrated, mounted, and set-up for the new LAMP system (diode laser and pressurized powder feeder). As shown in Fig. 2.6, a side-mount accessory with a 45° dichroic mirror

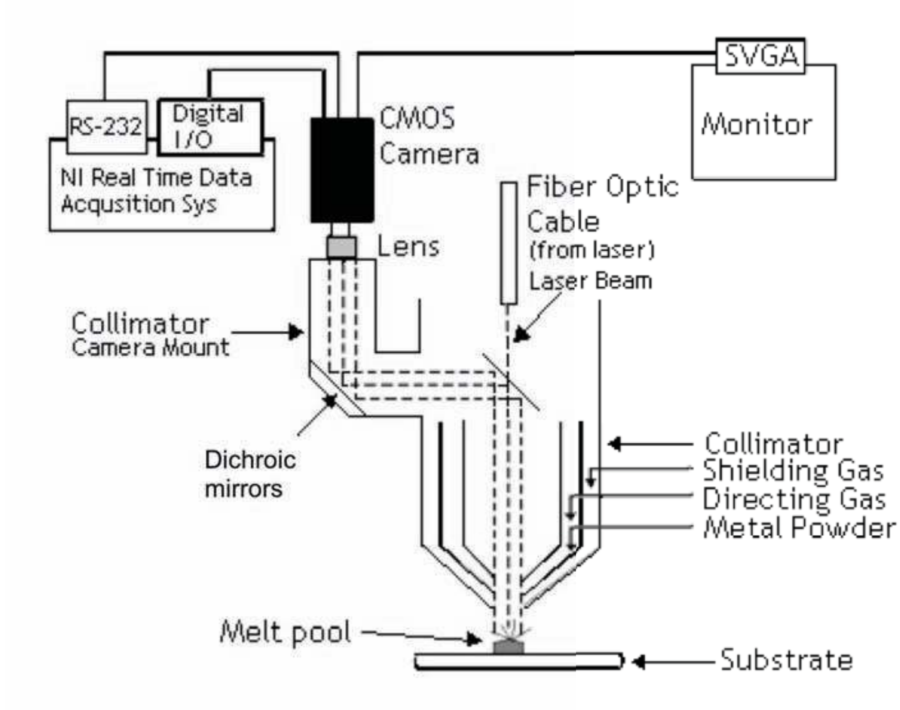

Figure 2.6: Vision System Location in LAMP System

and iris was added to the laser cladding head to allow axial vision of the melt pool. The set-up for data acquisition was at 90° to the melt pool and taking samples every 0.2 s. Preliminary tests, using black paper with white dots and ellipses of various sizes, were performed to ensure the camera was correctly aimed at the melt pool. During these tests the gain, offset, offset max and min, and AD max and min values were adjusted. However, all sets of values were unsatisfactory. It was determined that the 808 nm diode laser was saturating the vision sensor, not allowing the melt pool to be seen accurately.

To fix the saturation issue two long pass filters were purchased to eliminate the laser wavelength but allow the infrared range to be seen. During filter implementation, the melt pool image was improved, but only for stationary imaging. When the substrate was in motion, the vision system could no longer discern the melt pool from the surrounding environment. The current status of *Phase 4* is calibration of the vision system with the new LAMP system. All other steps are excellent future work.

2.4 FUTURE WORK

Currently, the first two out of five LAMP automatic control system framework phases have been completed and the third and fourth have been researched. The fifth phase needs to be researched and implemented to finish the control framework. In order to complete *Phase 3* the list in Section 2.3 must be finished. SPC analysis of temperature data must be performed to determine whether the LAMP system is consistently in control, or too heavily reliant on the user and is out-of-control. If the system is in control then feedback will not be needed to control the system in real-time, it will only be needed to establish a warning system. The warning system will alert the user that the temperature is not within the expected range due to an assignable cause. An example of an assignable cause is an unexpected layer thickness due to incorrect build parameters, causing the temperature sensor to point at the layers below the melt pool after the first few layers have been deposited. If the system is deemed out-of-control then closed-loop methods, such as a Proportional Integral Derivative (PID) controller, can be utilized to regulate the melt pool temperature.

To complete *Phase 4* the list in Section 2.4 must be finished. Preliminary tests to ensure proper functionality, such as imaging while the substrate is traversing, must be run. Then, a battery of tests can be performed to identify the common melt pool geometry during deposition of both H13 tool steel and Ti-64. During those tests the temperature sensor should monitor the melt pool temperature, which will allow for correlation between melt pool size/shape and temperature. Lastly, vision feedback can be utilized to establish a warning system and aid in the control of the LAMP system if it is out-of-control.

3. SUMMARY AND CONCLUSIONS

The manufacturing industry has been continuously changing over the past few decades with the introduction of technologies such as rapid prototyping, rapid manufacturing, lean manufacturing, flexible manufacturing, integrated systems, etc. All of these technologies also allow for faster production, less cost, higher quality products, less space, and so much more. Increasingly, computer technology is being implemented within traditional manufacturing equipment to make them easier to use and provide more functionality. Fully computer controlled or autonomous processes are the current direction of the industry as it provides better repeatability, reliability, and longer uptimes.

The University of Missouri-Rolla Laser Aided Manufacturing Process (LAMP) system is making profound strides in integrated systems research through the use of computer controlled processes. By focusing on creating an entirely automated Laser Metal Deposition (LMD) process, impressive designs are no longer exclusive to only those who have intimate knowledge of the LMD process. This thesis has shed light on the design strategy and methodology for building an integrated system capable of autonomous manufacturing. Imparting the lesser known elements required for building an integrated manufacturing system which are missing from current literature.

This thesis presents in Paper I, a scheme consisting of conceptual and physical integration steps and the salient five elements of an Integrated Freeform Manufacturing System (IFFMS). It was stressed that the conceptual design phase of the integration scheme was an integral part of achieving the manufacturing goal. Because design is a concurrent process, the elements of process planning, control system, motion system, Unit Manufacturing Process (UMP), and finishing process were explained to convey their importance and how they should be balanced. The major UMP families were explained so that a designer could recognize if a system has integration options. Additionally, a combination chart containing all five elements has been laid out for manufacturing system designers, in efforts to fulfill the need stated by the NRC UMP Committee. Furthermore, each step of the integration scheme was discussed to shed light on the construction of an IFFMS. Obstacles commonly encountered within the rapid prototyping branch of UMPs were presented along with a Laser Aided Manufacturing Process (LAMP) system case study. It was demonstrated that when the five IFFMS elements work together seamlessly, the resulting system achieves the desired manufacturing goal.

Paper II within this thesis presented a five phase framework for achieving an automated control system, which is geared toward integrated systems. The framework was modeled after the groundwork performed to control the LAMP system. By following the presented methodology for integrating hardware and software, individual manipulation and monitoring of LAMP components has been achieved successfully. To provide execution details of each phase of the framework, a six step methodology is also provided. Methodology steps one and two proved to be very helpful in alleviating many unseen problems that did not seem evident in the beginning. Preliminary results were demonstrated through successful deposition samples. The collected data presented in the results section of Paper II, demonstrates that *Phase 1* of the framework was successfully completed. Integration of the software package, real-time control system, and LAMP system components was confirmed to be imperative and achievable for the success of full automation.

Section 2 elaborates on the further development and results for the automatic control system framework presented in Paper II. Additionally, a change made to the framework was provided and explained. Establishing DNC communications or *Phase 2* was completed, which allows for the control system to send G&M codes to the CNC, while simultaneously controlling the laser power and powder feed rate, and monitoring feedback, all in real-time. The LAMP system now has the ability to make parts completely computer controlled. A major break-through for the integrated system, which has not been achieved in the past. Two example parts were shown, a basic thin wall structure (Fig. 2.3) and a hybrid tool path part that consists of four simple tool paths that are completed in unit layers (Fig. 2.3). Additionally, a listing of all steps that take place within *Phases 3* and *4* were given to illustrate the current progress and future work required to complete both. Currently in *Phase 3*, adding temperature feedback, several data samples of a similar tool path need to be collected to understand the temperature range for both H13 tool steel and Ti-64 powders. Due to the LAMP system laser upgrade, *Phase 4*, adding vision system feedback, is in the current process of sensor re-calibration after unsatisfactory results were attained in the preliminary tests. *Phase 5* has not been researched or begun, and is slated as future work for the overall successful conclusion of the framework.

Future work is required to complete the automatic control system framework and further validate the IFFMS scheme. Future work would include implementing the remaining listed steps for both *Phase 3* and *Phase 4* that have not been performed as outlined in Section 2.2 and Section 2.3, respectively. Once all the on-line phases are complete then the final phase that deals with the off-line process should be integrated into the control system. Thus, completing the framework. To further validate the IFFMS scheme, several case studies should be conducted. Either by applying the scheme to a new system that is in the works or to an existing system that could be retrofit. Moreover, the framework presented in Paper II could be utilized for developing the IFFMS control system element, which will further validate it as well. Once they are validated, the IFFMS scheme and control system framework can be used as trusted methods for manufacturing design.

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VITA

Jacquelyn Kay Stroble, daughter of Antoinette Yadrich and Ricky E. Stroble, was born on August 22, 1982 in Independence, Kansas. She graduated grade school and 11th in her high school class in Kansas City, Kansas. After high school, Jacquelyn attended Kansas City Kansas Community College on a Phi Theta Kappa Presidential Scholarship until 2002, graduating Magna Cum Laude with an A.S. in Engineering. Jacquelyn then transferred to the University of Missouri-Rolla to pursue a B.S. in Electrical Engineering and continued on to receive her M.S. in Manufacturing Engineering in May 2007.

During her undergraduate years at UMR, Jacquelyn spent three semesters on co-op working at Kimberly-Clark Corporation and taught the Electrical Engineering Factory Automation Laboratory during her final semester. Additionally, she received Honorable Mention for the National Eta Kappa Nu Alton B. Zerby and Carl T. Koerner Outstanding Senior ECE Student Award in 2005, for demonstrating outstanding scholastic excellence, high moral character and exemplary service to classmates, university, and community.

Jacquelyn is a member of the Society of Women Engineers (SWE), Institute of Electrical and Electronics Engineers (IEEE), Society of Manufacturing Engineers (SME), and the Order of the Engineer. She was inducted into Phi Theta Kappa International Honors Society in 2001, Tau Beta Pi Engineering Honor Society in 2003, Eta Kappa Nu Electrical Engineering Honor Society in 2003, and Phi Kappa Phi Honors Society in 2004. Jacquelyn served as corresponding secretary and president of SWE through the academic years of 2003-04 and 2004-05, respectively. She served as the bridge correspondent during the year of 2004 for Eta Kappa Nu and as the communications chair during the fall term of 2006.